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SOME EXPERIMENTS ON IMPACT-PRESSURE PROBES IN A LOW-DENSITY, HYPERVELOCITY FLOW

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ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

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a subsidiary of Sverdrup and Parcel, Inc.

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ABSTRACT

An experimental investigation of the behavior of flat-faced, impact-pressure probes with a range of orifice-to-probe diameter ratios was made in heated nitrogen, where Mach number was 9.3, stagnation temperature was 3000 °K, and the unit Reynolds number was 260/in. It was found, contrary to experience in low-density, unheated flows, that the impact pressure decreased with a reduction in orifice diameter for a fixed probe outer diameter in these tests. A discussion of the factors which could cause this decrease is contained herein. An analysis of the data indicates that in order to obtain as accurate a value of impact pressure as possible in low-density, hyp- . velocity flows, attention must be given to a number of factors, including viscous effects, thermal gradient effects, probe shape, thermal or chemical nonequilibrium, and non-continuum fluid phenomena.

CONTENTS

TABLES

ILLUSTRATIONS

NOMENCLATURE

A	Area
a	Speed of sound
C_D	Discharge coefficient
D	Outside diameter of the impact-pressure tube (see Table 1)
d	Orifice diameter
g	Gravitational constant
h	Enthalpy
I. D.	Inside diameter of the impact-pressure tube (see Table 1)
ℓ	Orifice length
M	Mach number
$\dot{m}$	Mass-flow rate
p	Pressure
q	Dynamic pressure
R	Gas constant, 3196.66 $ft^2/sec^2 \, ^\circ K$ for N^2
Re	Reynolds number based on probe outside diameter
S	Entropy
T	Temperature
U	Velocity
$\dot{w}$	Weight flow rate
Z	Compressibility factor
γ	Ratio of specific heats
λ	Mean free path
ρ	Density

SUBSCRIPTS

0	Reservoir conditions
1	Free-stream conditions
D	Outside diameter of the impact-pressure tube (see Table 1)

SUPERSCRIPTS

*	Conditions at the throat
'	Conditions downstream of the normal shock

INTRODUCTION

To date, surveys with impact-pressure probes have been the main method used to determine the Mach number and other flow characteristics in low-density, hypervelocity wind tunnels. The accuracy of this method is primarily dependent upon the correct measurement of the "true" impact pressure. It has been shown in Refs. 1 through 4 that when the Reynolds number, based on free-stream velocity, viscosity, and probe diameter, falls below some limiting value then the measured impact pressure deviates from the correct pressure because of the effects of viscosity.

Sherman (Ref. 1) made an extensive investigation into the performance of source-shaped and thin-lipped probes. As a result of these tests he produced curves showing how the measured impact pressure varied with probe Reynolds number, for Reynolds numbers from 20 to 1000 and Mach numbers from 1.7 to 3.4. Enkenhus (Ref. 2) extended the data for the thin-lipped probes down to a Reynolds number of 3 in the Mach number range from 1.2 to 2.

Thin-lipped probes seem to be in more common use than the source-shaped probes for the following reasons: 1) ease of manufacture, 2) less sensitivity to angle of attack and yaw, and 3) the viscous effects appear to be negligible down to a lower probe Reynolds number than for the source-shaped probes. An objection to the use of thin-lipped probes has been the existence of a region of initially decreasing impact pressure preceding the later rapid rise in pressure as the Reynolds number is reduced.

Clayden (Ref. 3) determined the effect of viscosity on a series of flat-faced probes having an orifice-to-probe diameter ratio of 0.333. It was demonstrated that this type of probe performed in a similar manner to the thin-lipped probes at a Mach number of 3.5 and over a Reynolds number range from 22 to 330. Some further tests in a conventional supersonic wind tunnel indicated the complete agreement between thin-lipped and small-bore, flat-faced probes in a flow regime where the viscous effects were nonexistent.

Matthews (Ref. 4) tested a series of flat-faced probes with a bore-to-probe diameter ratio of 0.4 over a Reynolds number range from 80 to 6000 and at a nominal Mach number of 5.6. These tests showed that the measured impact pressure was less than the ideal value for $80 \leq Re_D \leq 3000$, but that for $Re < 80$ it was greater than the ideal value.

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Based on test results reported to date, there remains a need for further data concerning factors affecting impact-pressure probes at low Reynolds numbers. Therefore, an investigation was conducted to determine the viscous effects on impact probes in the Low-Density, Hypervelocity (LDH) Wind Tunnel at the Arnold Engineering Development Center (AEDC), Air Force Systems Command. In the present series of tests in the LDH tunnel, in which low-density conditions occur at high temperatures and velocities, attention was confined primarily to a series of flat-faced probes having the range of orifice-to-probe diameter ratios shown in Table 1.

APPARATUS AND METHOD

WIND TUNNEL DESCRIPTION AND PERFORMANCE

The AEDC Low-Density, Hypervelocity Wind Tunnel is a continuous-flow, high-enthalpy wind tunnel. A photograph of the tunnel and a schematic drawing identifying the major components are given in Figs. 1 and 2, respectively. A complete description of the LDH tunnel is given in Ref. 5.

The arc heater is a 40-kw Thermal Dynamics unit which is usually operated at less than 20 kw with nitrogen as the working gas. Associated with the high gas temperatures is the need to cool several of the tunnel components, e.g., the plasma torch, settling chamber, and nozzle. Inherent in the cooling of these components is the resulting loss in the overall heating efficiency. The torch alone has an efficiency of approximately 60 percent, whereas the overall heating efficiency is between 10 and 15 percent with the present large settling chamber.

The aerodynamic nozzle exhausts into a large test chamber which is kept at a low pressure by means of two air ejectors coupled with the pumping system of the von Kármán Gas Dynamics Facility (VKF), AEDC intermittent wind tunnels. This large chamber permits the installation of a traversing mechanism and most of the force and pressure instrumentation in a vacuum environment. Prior to the present series of tests an investigation of the nozzle flow properties, using

nitrogen as the working gas, indicated that the following free-stream properties exist, if it is assumed that the gas is in thermal equilibrium:*

M_1	9-11.4
U_1	7000-10,000 fps
q_1	0.015-0.030 psia
Re_1	220-420/in.
T_o	2000-4000 °K
p_o	12-18 psia
λ_1	0.074-0.12 in.

The calculation procedure for estimating these flow conditions is outlined in the Appendix.

GAS FLOW CONTROL AND MEASUREMENTS

The gas used in the test is supplied in bottles under a pressure of approximately 2000 psia. Measurements of the dryness of the gas have indicated a dew point of approximately -40 °F. Tests at lower dew point temperatures have shown little or no effect on the nozzle flow properties.

The gas flows from the supply bottle, through a pressure regulator, which reduces its pressure to 150 psia, then through a needle valve followed by a sharp-edged orifice, and then into the stilling chamber. The pressures upstream and downstream of the orifice are measured with 150- and 60-psid pressure transducers, respectively. Since the pressure ratio across the orifice is always supercritical the flow through the orifice is directly proportional to the upstream pressure. An accurate mass-flow calibration rig was constructed to calibrate the orifice. The resulting calibration showed the expected linear relationship between orifice upstream pressure and mass flow. A thermocouple upstream of the orifice measured the supply temperature.

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*The possibility of vibrational nonequilibrium in the LDH Tunnel was discussed in Ref. 5, and the changed flow conditions corresponding to frozen flow were estimated. In the present case, the effect on Reynolds number is most important. However, unit Reynolds number behind a normal shock is virtually unchanged by the assumption of frozen vibration under these conditions.

RESERVOIR TEMPERATURE

Since no accurate means of measuring reservoir temperature directly are available, an indirect method involving a knowledge of the nozzle mass flow and the stilling chamber pressure was used. (A resumé of this method is given in the Appendix.) The reservoir pressure is sensed by a wall tap and measured by a 30-psid transducer.

PRESSURE MEASURING SYSTEM

In the measurement of low pressures the time for the pressure in the sensing element to stabilize is a function of the length and bore of the tube connecting the probe to the transducer and also the volume of the transducer. Because of the variety of probes tested in the present series of tests it was not possible to keep the lag time to a minimum in all cases. The main components of the pressure measuring system are:

1. Transducer
2. Scanner valve
3. Reference and calibration pressure systems
4. Micromanometer and McLeod gage.

Some of the components of this system are shown in Figs. 3 and 4. Wherever possible, metal tubes and silver soldered joints were used in order to minimize outgassing effects. In cases where it was necessary to use flexible tubing (metal, rubber, or tygon) its length was kept to an absolute minimum.

TRANSDUCER

The gage currently in use is a Northam DP-7 variable-reluctance differential-pressure transducer with an operating range of ±0.15 psid. This transducer has a small internal volume, a rapid response time, and a linear relationship between output voltage and differential pressure. As the temperature of the transducer was raised there was a zero shift but no measurable change in the slope of the pressure-voltage curve.

SCANNER VALVE

A Giannini scanner valve, modified to improve its response characteristics in the low-density regime, was used. In its standard condition this valve contains twelve small ports; in its modified condition this number was reduced to six and their diameters increased. Of the six ports, one was taken up by the transducer reference pressure, another by the calibration pressure, leaving four ports available for general pressure measurements.

The transducer is mounted directly on the scanner valve (see Fig. 3), and both are mounted within the test chamber. There are two main advantages to this: 1) the length of the tubing from the probe to the transducer is kept small, and 2) by placing the pressure system in a vacuum environment, because of the small pressure differential that exists, the effect of any leaks in the pressure measuring system is minimized.

REFERENCE AND CALIBRATION PRESSURE SYSTEMS

Two pressure headers are installed through the side of the test chamber and connected to the transducer through the Giannini valve. Each of these headers is connected to an oil diffusion pump. These pumps are capable of maintaining a pressure of 0.01 micron Hg in each of the headers. However, under normal operating conditions only the reference pressure header is kept at this pressure. When the tunnel is not in use this pressure is applied to both sides of the transducer and micromanometer. In this way these two instruments are kept well outgassed at all times. A differential pressure can be applied to the transducer by closing off the pressure header from its oil diffusion pump by means of a gate valve and raising the pressure by means of a controlled leak. The resulting pressure differential is measured with the micromanometer.

MCLEOD GAGE AND MICROMANOMETER

A Manostat McLeod gage is used to measure the reference vacuum pressures. This gage is kept at the reference pressure at all times in order to reduce any errors caused by outgassing.

The micromanometer is of the same design as that used in the low-density wind tunnel at the University of California (Ref. 6). A differential pressure of 0.001 in. of fluid can be detected with this

instrument. The fluid used in this instrument is Octoil S and was chosen primarily because of its low vapor pressure. A primary standard deadweight tester was used to calibrate the micromanometer, and the resulting calibration indicated that one in. of fluid displacement corresponded to a pressure of 1696 microns Hg at room temperature.

PRESSURE CALIBRATION PROCEDURE

The micromanometer and transducer readings are noted with the reference vacuum pressure applied to both sides of these instruments. The calibration header is then isolated from its oil diffusion pump by closing the gate valve. Then the pressure in this header is raised by means of a controllable leak. At this condition the micromanometer and transducer readings are noted. This procedure is repeated for a series of pressure differentials. Two typical calibrations are shown in Fig. 5 for the two pressure ranges of interest in this series of tests.

One of the main advantages of this technique is that the transducer can be calibrated at any time during a run. This is a valuable attribute in cases where lengthy run times exist.

TEST PROBES

As mentioned in the Introduction, this report is primarily concerned with flat-faced, uncooled probes having various outside diameters together with a range of inside diameter-to-outside diameter ratios. A brief investigation into the effect of probe wall temperature was made with a series of four water-cooled probes. Figure 6 shows some typical probes installed on the rotary probe carrier. Table 1 gives the dimensions of all the probes investigated in this test program.

ROTARY PROBE HOLDER

In order to facilitate the testing of the large number of probes and also to increase the probability of maintaining the same test section flow conditions, a multi-tube probe holder was constructed. It is of the same form as the rotary probe holder described in Ref. 1.

The probe holder can carry eight probes and is hand operated from outside the tunnel by means of a flexible drive shaft coupled to a worm gear driving a gear attached to the probe holder. A counter attached to the worm gear determines the position of the probe

to within 0.1 deg. To facilitate the mounting and manufacture of the probes, a quick-break O-ring joint was used at the ends of the rotary holder spokes. Because of the high temperatures experienced at this joint a Viton O-ring having good high temperature qualities was used. At the end of each run these O-rings were replaced to ensure that no leaks caused by O-ring deterioration could occur. A quad-ring provided a seal between the movable and fixed parts of the holder. A photograph of the holder is shown in Fig. 6.

One of the disadvantages of this rotary probe holder is the large volume it introduces into the pressure measuring system. For some of the smaller probes under investigation it was necessary to mount them directly to the transducer in order to reduce the lag time to reasonable proportions.

PROBE DRIVE MECHANISM

The rotary probe holder is mounted on the probe traversing mechanism which provided it with both axial and lateral movements. The drive mechanism is driven by two 1/20-hp electric motors mounted outside the tunnel. This enables the probe to be positioned to within 0.01 inch in either the axial or lateral directions.

TUNNEL OPERATING CONDITIONS

Prior to the present tests, the nozzle flow was surveyed with both impact and static probes to determine the extent of the useable flow region. The limitations of the present pumping system preclude the possibility of operating with a balanced jet, i.e., an equality of the free-stream and test chamber pressures. A disadvantage of operating under these conditions is that there is always an axial Mach number gradient. However, this is not considered to be a serious defect in this series of tests since the main interest is in conditions at the probe face. Figure 7 shows the variation of impact pressure along the nozzle centerline for a range of test chamber pressures. A radial survey of impact pressure at the nozzle exit plane indicates that there is a region of uniform flow of approximately 0.4-in. diam (Fig. 8). A static pressure probe survey within this region of uniform flow indicated a constant static pressure across the uniform core.

The flow conditions at the nozzle exit plane during this experiment were found by the method of the Appendix and are:

M_1 = 9.3	λ_1 = 0.0768 in.
U_1 = 8600 ft/sec	T_o = 3020°K
p_1 = 21.9 microns Hg	ρ_1 = 3.163×10^{-6} lb/cu ft
T_1 = 193°K	q_1 = 3.63 lb/sq ft
	Re_1 = 260/in.

for an isentropic stagnation pressure of 17.79 psia and nitrogen gas.

PROCEDURE

The desired nozzle flow is established by adjusting the flow rate and power input to the arc heater to bring the stagnation conditions to the operating level. By adjusting the air ejectors and the air bleed valve the test chamber pressure is brought to the correct level. With the tunnel at the correct operating condition the probe being tested was brought to the exit plane of the nozzle on the nozzle centerline. After a suitable time interval, to allow the pressure in the pressure measuring system to achieve the equilibrium value, the pressure was noted. The test chamber pressure was monitored throughout the tests to ensure that the nozzle shock was always downstream of the exit plane.

Experience in operating this tunnel has indicated that when the stagnation pressure and mass flow were kept at the same values for each run, then test section impact pressures were repeatable to within ±30 microns Hg or ±1.3 percent. This degree of accuracy was confirmed by repeating tests of various probes at odd intervals throughout the test program which extended over several weeks.

DISCUSSION OF RESULTS

The results of the present experiments are shown plotted in Fig. 9 and tabulated in Table 2. It should be noted that the measured impact pressure is plotted versus the orifice-to-probe diameter ratio for each of the probe diameters under investigation. For each probe tested there seems to be a value of this ratio below which the measured impact pressure decreases. It is felt that this behavior is of sufficient significance to warrant some discussion.

It has been stated in Ref. 7 that at supersonic speeds the true impact pressure will not be measured unless the orifice is small in

comparison with the frontal area of the probe. It is assumed that the measured pressure is the mean value over the area of the orifice, this being less than the true impact pressure, for finite orifices. This is possibly somewhat of a simplification since it is also stated in the above reference that the flow in the vicinity of the orifice is complicated and that there may be a rotational flow within the orifice which produces an effect on the pressure. In Ref. 8, a theoretical analysis of the effect of probe diameter and orifice size does, in fact, indicate that there is a rotational flow within the pressure orifice. Furthermore this theoretical analysis does show that the measured pressure is always less than the true impact pressure for the orifice size considered. Some experimental studies (Refs. 1 and 10) on impact probes indicate that with a reduction in orifice size the measured pressure increases.

In Ref. 1 where a series of source-shaped probes having orifice-to-probe diameter ratios of 0.1, 0.2, and 1.0 were tested, it was shown that the measured impact pressure decreased as this ratio increased. It must be emphasized, however, that this only appears to be true for Reynolds numbers based on probe diameters of less than approximately 200. At the higher Reynolds numbers the variation with orifice-to-probe diameter ratio no longer seems to follow a regular pattern. In this high Reynolds number region this variation of impact pressure tends to confirm the results of Ref. 3 where it was found that at Mach number of 3.5 and at a high Reynolds number a thin-lipped probe measured almost exactly the same impact pressure as a small-bore probe. However, though this may be true for Mach numbers less than 3.5 there is no reason to expect it to be true for the higher Mach numbers. In fact, consideration of Ref. 9 where a study is made of the pressure distribution over flat-faced bodies in the Mach number range $2.15 \leq M \leq 7.9$ indicates that for $M > 4.84$ the ratio of measured pressure at a radial station to the centerline value is less than for $M = 2.15$. This would indicate that at the higher Mach numbers the orifice size may produce a more significant effect.

In Ref. 10, a study of the effect of orifice-to-probe diameter ratio for flat-faced probes in subsonic, low Reynolds number flow was made. It is of interest to note the increase in measured impact pressure with decrease of orifice-to-probe diameter ratio from 0.685 to 0.255. Since the flow between the shock and the probe face is essentially subsonic it would be expected that, qualitatively at least, these probes in supersonic, low-density flow should show the same trend with decrease in orifice diameter.

It was considered that this effect of orifice diameter was of sufficient interest to warrant further investigation in a high-density, high Mach number flow. The 12-in. Supersonic Tunnel located in the VKF was the only readily available tunnel in which to investigate this. Tests were carried out at M = 5 and at Reynolds numbers/in. from 0.7 to 3.17 x 10^5 with the 0.5-, 0.375-, and 0.125-in. flat-faced probes. The results of these tests, Fig. 10, show that in this flow regime the size of the orifice had no measurable effect on the measured impact pressure.

Based on the foregoing discussion, it would seem reasonable to conclude that reducing the orifice size for a particular probe diameter should not of itself reduce the measured impact pressure, at least on flat-faced probes. Because of this it was necessary to consider other factors which may influence the measured impact pressure.

In Ref. 2 an analysis of the impact probe in free-molecule flow is presented. This analysis shows the strong dependence of the measured pressure on the length-to-diameter ratio of the probe; as this ratio increases the measured pressure increases. A test with two 0.25-in. O.D. water-cooled probes having an orifice diameter of 0.0145 in. and orifice lengths of 0.0005 and 0.0625 in. indicated that the shorter orifice measured a pressure 4 percent lower than the longer one. This result is in qualitative agreement with the above theory but differs considerably in magnitude from the predicted effect, presumably because the flow was not truly free-molecular. Since the direction of this free-molecular flow effect on measured pressures is opposite to the experimentally observed trend of the data, it is indicated that the pressures sensed by the probes were not dominated by parameters which are significant in free-molecule flow theory.

In the absence of any firm indications to the contrary, it has been tentatively assumed that the flow in the nozzle is in thermal equilibrium. However, when consideration is given to the relaxation time (Ref. 11) for nitrogen after the normal shock ahead of a typical probe, it is apparent that the flow between the probe and the shock may have its vibrational mode frozen. An analysis of the effect of the freezing of the vibrational mode indicates that this does not affect interpretation of the impact-pressure measurements to a significant degree in the present case. Furthermore, it would not be expected that freezing of the flow in this region would affect the pressure as sensed by a range of orifice sizes in a probe of fixed outside diameter since the distance from shock to probe would remain constant (see the Appendix).

Another factor which could influence the probe readings would be the temperature difference existing between the probe face and the pressure transducer. In Refs. 12 and 13 Howard presents some

experimental and theoretical data concerning this effect. In the work reported in Refs. 12 and 13, gas temperature and probe wall temperature were equal. However, this was not necessarily the situation in the LDH Tunnel. In the present test series, two sets of 0.25-in.-diam probes, each with identical values of orifice diameter, were tested, one set being uncooled except by natural conduction and radiation and the other being water-cooled, as shown in the sketch with Table 1. This means that in one case a substantial temperature difference between the probe face and the transducer existed, whereas in the other case no such difference existed. In considering these probes, however, it must be realized that the sensing orifice is so short in length that there could not be a significant wall temperature difference along the short length of a small-bore orifice. Furthermore, the second tube in these probes is of such a diameter that an extremely large temperature difference would be required to produce a significant correction. A comparison of the two series of tests is shown in Fig. 11. The fact that there is a very small difference between the two sets of data for widely differing wall temperatures would seem to indicate that some temperature other than probe wall temperature is the significant parameter, if temperature difference is, indeed, a reason for the fall in pressure at low orifice-to-probe diameter ratios.

Probstein and Kemp (Ref. 14) have presented a theoretical analysis of the flow conditions existing near the stagnation point of a blunt body in a hypersonic, rarefied gas flow. Perhaps the most significant result from this analysis, as far as the present investigation is concerned, is the predicted decrease in impact pressure as the Reynolds number decreases within the incipient merged layer regime. Furthermore, it is shown that the impact pressure on a highly cooled body is greater than that on an insulated body. This could explain why in the present series of tests the cooled probes measured a slightly higher impact pressure than the uncooled probes.

Three flow regimes are defined in Ref. 14:

(1) Incipient merged layer regime where

$$\frac{2\lambda_1}{D} \ll 1.0$$

(2) Fully merged layer regime where

$$\frac{2\lambda_1}{D} < 1.0$$

(3) Transitional layer regime where

$$\frac{2\lambda_1}{D} > 1.0$$

These equations are strictly valid only when the body has a hemispherical nose such that the nose radius of curvature is equal to the

body radius, i. e., a hemisphere-cylinder. For the case of flat-faced bodies it can only be assumed that the effective nose radius of curvature is greater than the body radius but less than infinity. With this assumption the test data span the three regimes listed above. However, depending on what value is assumed for the shock radius of curvature, it can be shown that the test results lie wholly within regimes (2) and (3). If this is the case then the impact pressure measured with even the 0.5-in.-diam probe is not the ideal impact pressure. Because of the decrease in impact pressure with decrease in Reynolds number, in the incipient merged layer, this value could be less than the true value. However, this does not seem likely because of the very large effective nose radius of curvature of a flat-faced body.

Although this analysis shows that for a fixed geometry probe a decrease in impact pressure with decrease in Reynolds number is possiblé, it does not account for the decrease in impact pressure with reduction in orifice size for a fixed probe diameter, shown by the present test data. However, it may explain in part the reduction in impact pressure shown by the data contained in Ref. 4. That it does not provide a complete explanation is shown by consideration of Sherman's results for source-shaped and thin-lipped probes. In these tests it was shown that the source-shaped probes did not show a significant reduction in impact pressure with decrease in Reynolds number, whereas the thin-lipped probes did.

Another factor in the analysis of impact probe data may be the temperature difference that exists between the gas at the orifice inlet and that at the back of the orifice. It was not possible in the present studies to measure these temperatures, but from a measurement of the wall temperature at the front of the probe, it would seem reasonable to assume that a temperature difference in the gas of 1500°K could occur. If this were the case, a thermal transpiration effect of both sufficient magnitude and direction to account for the decreasing impact pressures should exist. By using this temperature difference in conjunction with Howard's data, Refs. 12 and 13, an allowance for such an effect was calculated. Impact pressure with this arbitrary correction applied is shown in Fig. 12 together with the uncorrected data. A comparison of the present results with those of other tests is made in Fig. 13. It should be noted that the arbitrarily corrected data more nearly agree with other test data on flat-faced probes. However, this agreement may be coincidental since there is no reason why the relationship between impact pressure and Reynolds number should be the same for such widely varying test conditions.

CONCLUSIONS

It has been shown that for a fixed impact probe diameter, decreasing the size of the pressure sensing orifice caused a decrease in the measured pressure. This is at variance with test results at other Mach numbers in unheated flows. A series of tests in an M = 5 high-density airstream indicated that the measured impact pressure was constant over a range of orifice-to-probe diameter ratios from 0.08 to 0.97.

It is apparent that in low-density flows it is not sufficient to confine attention to the probe Reynolds number based on outside diameter, but one must consider carefully the size of the pressure sensing orifice. In heated, low-density flows there appears to be a marked effect on the measured impact pressure as the Knudsen number of the orifice increases. It is tentatively suggested that the decrease in measured impact pressure as orifice size decreased for a probe of fixed outside diameter in the tests reported is mainly attributable to a temperature difference between the gas at the orifice face and the back of the orifice, creating a thermal transpiration effect.

From the present tests it would appear that in order to measure as nearly a true impact pressure as possible in low-density, hypervelocity flows, the probe Reynolds number and the orifice must be as large as is practically possible if any of the extraneous effects mentioned above are expected to be important.

REFERENCES

1. Sherman, F. S. "New Experiments on Impact Pressure Interpretation in Supersonic and Subsonic Rarefied Airstreams." "Univ. of California Inst. of Engr. Res., HE-150-99, December 1951.

2. Enkenhus, K. R. "Pressure Probes at Very Low Density." Institute of Aerophysics, Univ. of Toronto, UTIA. Rept. No. 43, January 1957.

3. Clayden, W. A. "Preliminary Experiments on Pitot Pressure Interpretation of Small-Bore Square-Ended Probes in Low Density Flow." International Symposium on Rarefied Gas Dynamics, Proceedings, July 2-5, 1958, Permagon Press, 1960, pp. 32-37.

4. Matthews, M. L. "An Experimental Investigation of Viscous Effects on Static and Impact Pressure Probes in Hypersonic Flow." Guggenheim Aeronautical Laboratory, Calif. Inst. of Tech., GALCIT-M-44, June 2, 1958.

5. Potter, J. L., Kinslow, M., Arney, G. D., Jr., and Bailey, A. B. "Description and Preliminary Calibration of a Low-Density, Hypervelocity Wind Tunnel." AEDC-TN-61-83, August 1961.

6. Mashlach, G. J. "A Precision Differential Manometer." The Review of Scientific Instruments, Vol. 23, No. 7, pp. 367-369.

7. Chambre', P. L. and Schaaf, S. A. "The Impact Tube." Physical Measurements in Gas Dynamics and Combustion, Princeton University Press 1954, pp. 111-123.

8. Lèster, W. G. S. "The Flow Past a Pitot Tube at Low Reynolds Numbers." Aeronautical Research Council (Gt. Brit), A. R. C. 22070, July 11, 1960.

9. Chones, A. J. "Heat-Transfer and Pressure Measurements on Flat-Faced Flared-Tail Circular Cylinders and Normal Disks." U. S. Naval Ordnance Laboratory, NAVORD Rept. 6669, June 15, 1959.

10. Schowalter, W. R. and Blaker, G. E. "On the Behavior of Impact Probes at Low Reynolds Numbers." Journal of Applied Mechanics, March 1961, pp. 136-137.

11. Blackman, Vernon. "Vibrational Relaxation in Oxygen and Nitrogen." Journal of Fluid Mechanics, Vol. 1, Pt. 1, May 1956, pp. 61-85.

12. Howard, Weston M. "An Experimental Investigation of Pressure Gradients Due to Temperature Gradients in Small Diameter Tubes." Guggenheim Aero. Lab., Cal. Inst. of Tech., GALCIT-M-27, June 1955.

13. Howard, Weston M. "The Effect of Temperature on Pressure Measured in a Hypersonic Wind Tunnel." Jour. Aero/Space Sciences, Vol. 26, No. 11, November 1959, pp. 764.

14. Probstein, Ronald F. and Kemp, Nelson H. "Viscous Aerodynamic Characteristics in Hypersonic Rarefield Gas Flow." Jour. of the Aero/Space Sciences, Vol. 27, No. 3, March 1960, pp. 174-192.

15. Hilsenrath, Joseph. "A First Approximation to the Thermodynamic Properties of Nitrogen." National Bureau of Standards Unpublished Preliminary Draft, May 1959.

16. Lewis, C. and Norton, B. B. Personal Communication, Feb. 1961.

17. Ames Research Staff. "Equations, Tables, and Charts for Compressible Flow." NACA Rept. 1135, 1953.

APPENDIX

CALCULATION PROCEDURE FOR DERIVING THE FLOW PROPERTIES IN THE LOW-DENSITY, HYPERVELOCITY WIND TUNNEL

The calibration of low-density, supersonic, unheated gas flows presents problems because of the difficulty experienced in measuring such quantities as static pressure, density, heat transfer, and shock angle. These problems are more serious when, in addition to the low-density condition, a high total temperature is introduced as well.

In the following sections an outline of the procedures used to define the reservoir temperature and the flow properties in the working section are given.

RESERVOIR TEMPERATURE

Because of the high temperatures in the stilling chamber, or reservoir, it has not been possible thus far to make a direct measurement of this temperature. However, an indirect calculation of the temperature has been made by two methods based on the measured reservoir pressure and mass-flow rate. In both these methods it is assumed that the discharge coefficient of the aerodynamic nozzle throat is unity and that sonic flow exists at the station of minimum area.

Method I

Mass-flow rate at the sonic throat can be written:

$$\dot{m} = C_D \rho^* A^* a^* \tag{A-1}$$

or

$$\dot{w} = C_D \rho^* A^* a^* g \tag{A-2}$$

For flow in thermodynamic equilibrium this can be rewritten as:

$$\dot{w} = C_D A^* g \frac{\rho^* a^*}{\rho_o a_o} \frac{p_o}{Z_o R T_o} \sqrt{\gamma_o R T_o Z_o} \tag{A-3}$$

For nitrogen at temperatures less than 3,500°K and pressures on the order of one atmosphere the compressibility factor, Z, is very nearly

equal to unity. If, in addition, it is assumed that γ is constant such that:

$$\frac{\rho^*}{\rho_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}} \tag{A-4}$$

$$\frac{a^*}{a_o} = \sqrt{\frac{T^*}{T_o}} = \sqrt{\frac{2}{\gamma + 1}} \tag{A-5}$$

it follows that:

$$T_o = C_D{}^2 \, (A^* g)^2 \left(\frac{p_o}{\dot{w}}\right)^2 \frac{\gamma}{R} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}} \tag{A-6}$$

For the LDH Tunnel, with the assumption that the discharge coefficient is equal to unity, this reduces to:

$$T_o = 280.634 \, \gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}} \left(\frac{p_o}{\dot{w}}\right)^2 \tag{A-7}$$

where p_o is in psia and $\dot{w}$ is in lb/hr. Equation (A-6) indicates the dependence of the reservoir temperature on the nozzle throat discharge coefficient. Furthermore, this equation is only valid for a constant value of γ. Thus, for flows of fluids at high temperatures it is necessary to select an effective or average value of γ between the reservoir value and that at the throat. The variation of reservoir temperature with reservoir pressure and mass flow over the present operating regime of the LDH tunnel is shown in Fig. A-1

Method II

In this method it is assumed that the flow process from the reservoir to the throat is isentropic and also of constant total enthalpy. Furthermore, as in the above method, it is assumed that the aerodynamic throat has a discharge coefficient of unity. Thus:

$$h_o = h^* + 1/2 \, a^{*2} = \text{constant} \tag{A-8}$$

$$S_o = S^* = \text{constant} \tag{A-9}$$

In a thermally perfect (Z = 1) gas expanding at constant entropy, ρ^* and a^* are entirely determined by reservoir pressure and enthalpy or temperature. Therefore by using Eq. (A-2) with $C_D = 1$ the weight flow, $\dot{w}$, is determined. The thermodynamic data for nitrogen used in these calculations is given in Ref. 15. Thus a curve relating reservoir pressure and mass flow can be derived and is shown in Fig. A-1.

This result may be obtained over the range of conditions where enthalpy and temperature are uniquely related. Where this is not the case the ratio $p_o/\dot{w}$ is a function of T_o and p_o. This point is emphasized so that no extrapolation to the existing curve is made.

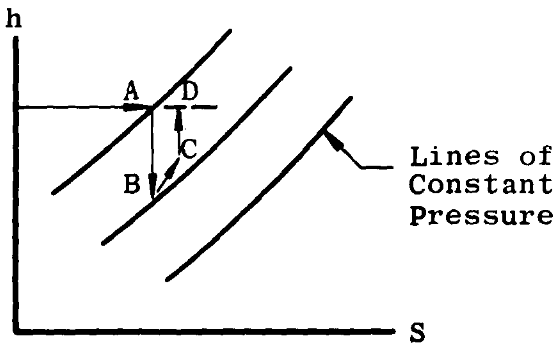
Of the two temperature estimates, in principle, the value derived from the Mollier diagram is the more accurate. Some detailed measurements of reservoir enthalpy of the heated gas with a series of calorimeters have confirmed the validity of the above analysis. Also, it has been established that the discharge coefficient of the tunnel nozzle is unity.

CALCULATION OF OTHER FLOW PROPERTIES

Use of the impact-pressure probe represents the most straightforward method of flow calibration. Part of the calibration of the flow properties in the LDH Tunnel is based on an impact-pressure reading and assumed thermodynamic equilibrium of the gas with an isentropic, constant total enthalpy expansion from the reservoir conditions.

A water-cooled probe with an outside diameter of 0.25 in. and an inside diameter of 0.095 in. was used to survey the flow in the nozzle. It was considered that with such a probe the viscous and thermal gradient effects should be small.

The flow process through a supersonic nozzle is shown below.



A-B Isentropic expansion from the reservoir to a position just upstream of the probe normal shock

B-C Flow through the shock, an increase in entropy

C-D Isentropic compression, that is, from just downstream of the normal shock there is an isentropic compression to the stagnation condition at the probe

A-C It is assumed that the process is one of constant total enthalpy and provided there is equilibrium and no dissociation, it is also a constant total temperature process ($T_o = T_o'$). However, if there is dissociation or nonequilibrium then $T_o \neq T_o'$.

Normal shock tables for nitrogen have been computed for a range of temperatures and pressures (Ref. 16). Calculation of the flow parameters is then possible using these data and the thermodynamic data contained in Ref. 14.

The normal shock tables give values of h_o, T_1, T_2, p_1, p_2, M_1, V_1, M_2, ρ_1, ρ_2, S_1, and S_2. Entering the Mollier diagram at a known stagnation enthalpy and the entropy upstream and downstream of the normal shock, i.e., S_1 and S_2, the values of the reservoir pressure, p_o, and impact pressure, p_o', can be found. In this manner the variation of impact pressure with reservoir pressure for a range of Mach numbers and reservoir temperatures can be found. Thus for a particular reservoir pressure the variation of impact pressure with Mach number for a range of reservoir temperatures can then be found. A similar method is used to determine the variation of the other properties, ρ_1, ρ_2, p_1, p_2, etc., with Mach number and reservoir temperature. Independent measurements of static pressure and local mass flux per unit area have confirmed the results of the impact-pressure measurements.

NONEQUILIBRIUM EFFECT ON IMPACT PRESSURE

As stated previously, there is no clear evidence that the flow in the nozzle is or is not in equilibrium. However, the flow between the probe face and its normal shock can, with a fair degree of certainty, be assumed to have its vibrational mode frozen. A method of calculating the magnitude of this effect on measured impact pressure is given below.

If flow in the nozzle is in equilibrium the ratio of static pressure to impact pressure in the test section can be read off the curves, discussed in the previous section, for a particular Mach number, reservoir temperature, and pressure. Through the shock $\gamma = 1.4$ if the vibrational mode is frozen, so for the above Mach number the ratio of static pressure to impact pressure can be read from the tables of Ref. 17. Dividing this value by the equilibrium value obtained from normal shock tables for equilibrium flow illustrates the effect of this

degree of flow nonequilibrium upon the measured impact pressure. Calculations for typical flow conditions in the LDH Tunnel indicated that the measured value (i. e., a frozen value) is up to 4 percent greater than the equilibrium value in the Mach number range from 8 to 12 at a reservoir temperature of 3000°K. This order of change would mean that the true equilibrium Mach number is 9. 4 rather than the value of 9. 3 quoted in the text.

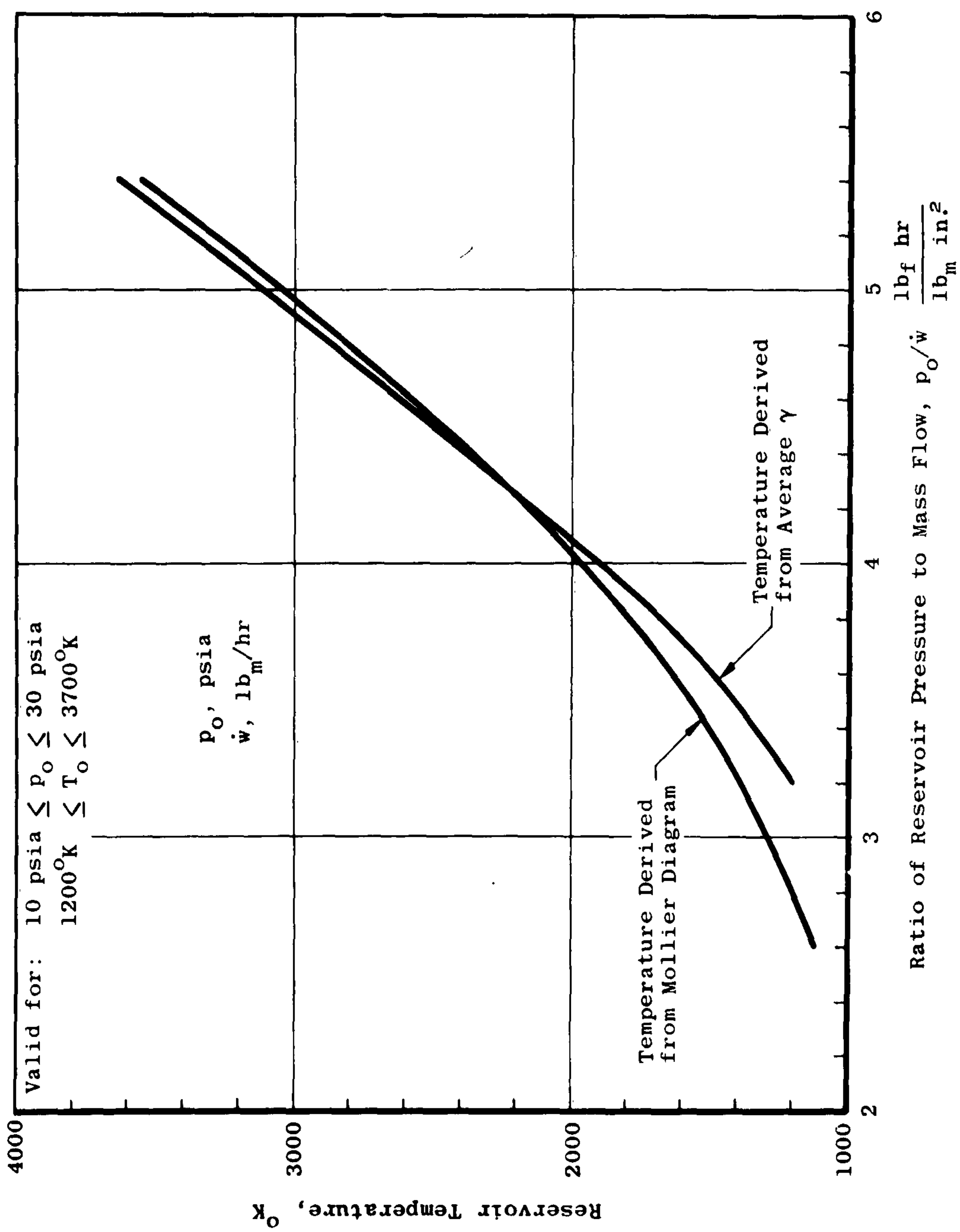
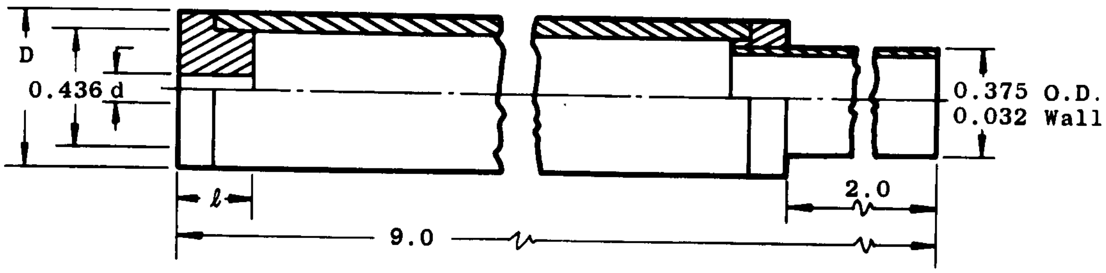
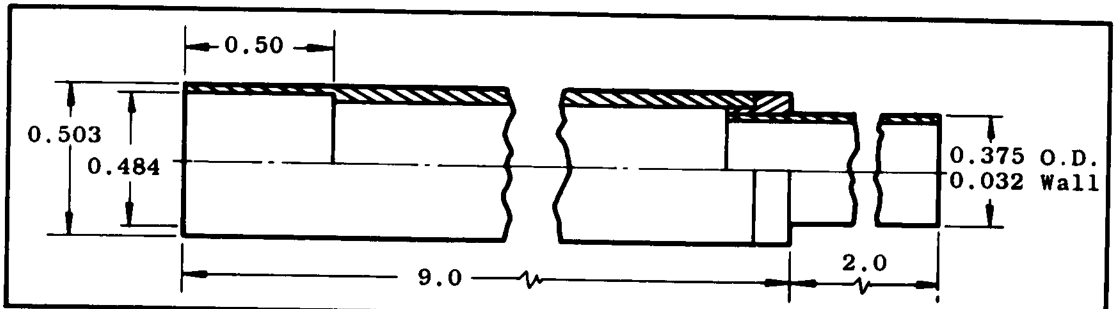


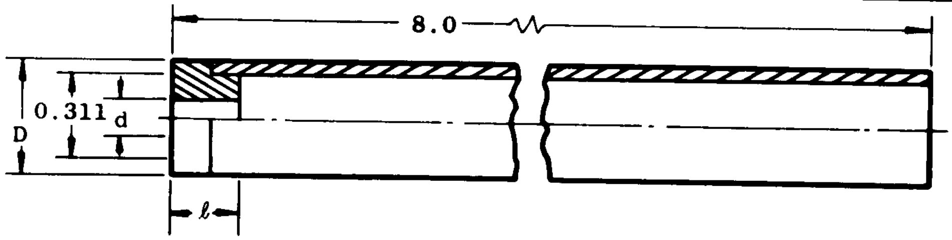
Fig. A-1 Reservoir Temperature

TABLE 1
TEST PROBES*



D	d	ℓ
0.502	0.055	0.250
0.500	0.104	0.250
0.496	0.152	0.250
0.499	0.250	0.250
0.501	0.375	0.250
0.501	0.436	7.0

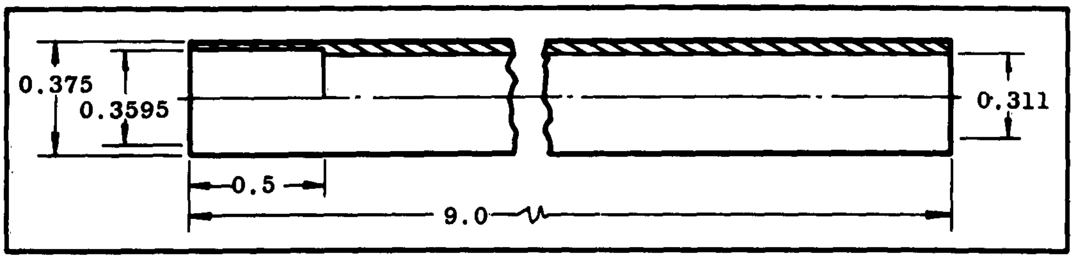


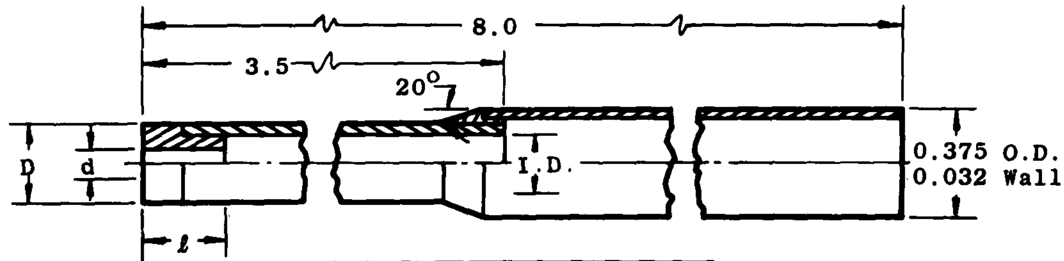


D	d	ℓ
0.375	0.032	0.125
0.377	0.0635	0.125
0.377	0.125	0.125
0.375	0.250	0.125
0.376	0.311	8.0

*Not to scale.
All Dimensions
in inches.

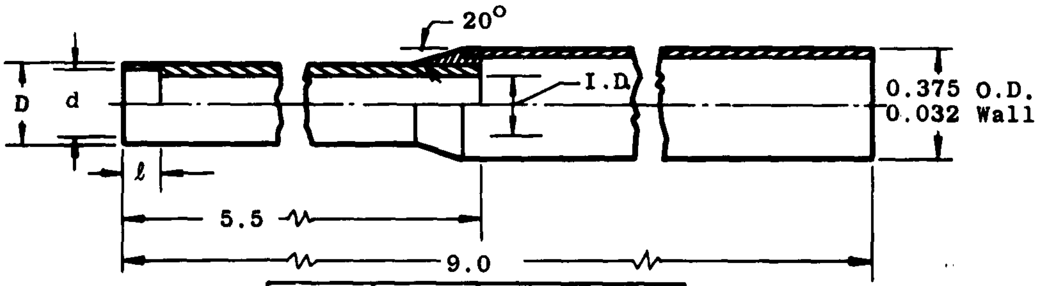
TABLE 1 (Continued)



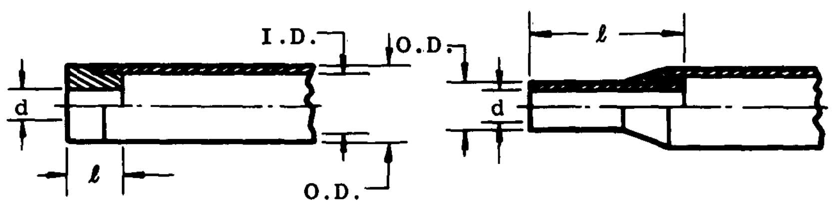


D	d	I.D.	ℓ
0.247	0.032	0.186	0.125
0.247	0.0635	0.186	0.125
0.247	0.125	0.186	0.125
0.248	0.186	0.186	3.5
0.1875	0.0635	0.1475	0.125
0.1875	0.1175	0.1175	3.5
0.1885	0.1475	0.1475	3.5
0.156	0.032	0.116	0.125
0.156	0.0635	0.116	0.125
0.156	0.116	0.116	3.5
0.1265	0.061	0.061	3.5
0.1265	0.085	0.085	3.5
0.1280	0.089	0.089	3.5
0.1265	0.095	0.095	3.5

TABLE 1 (Continued)



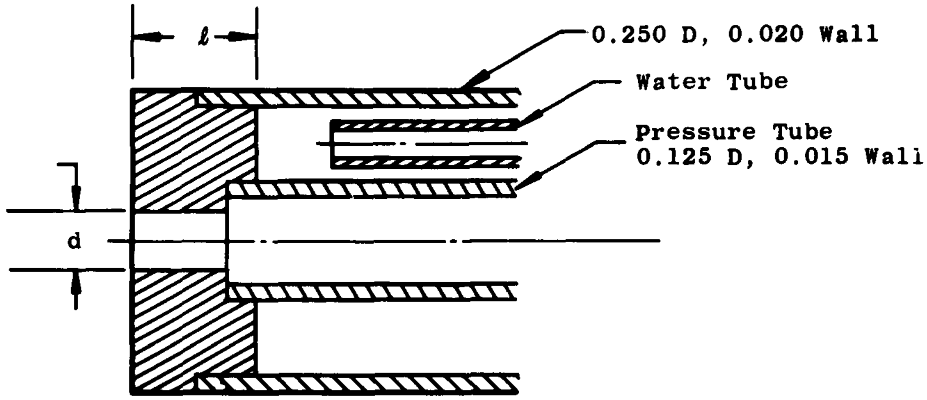
D	d	I.D.	ℓ
0.123	0.116	0.095	0.250
0.157	0.144	0.116	0.250
0.1845	0.178	0.1475	0.250
0.248	0.228	0.186	0.250



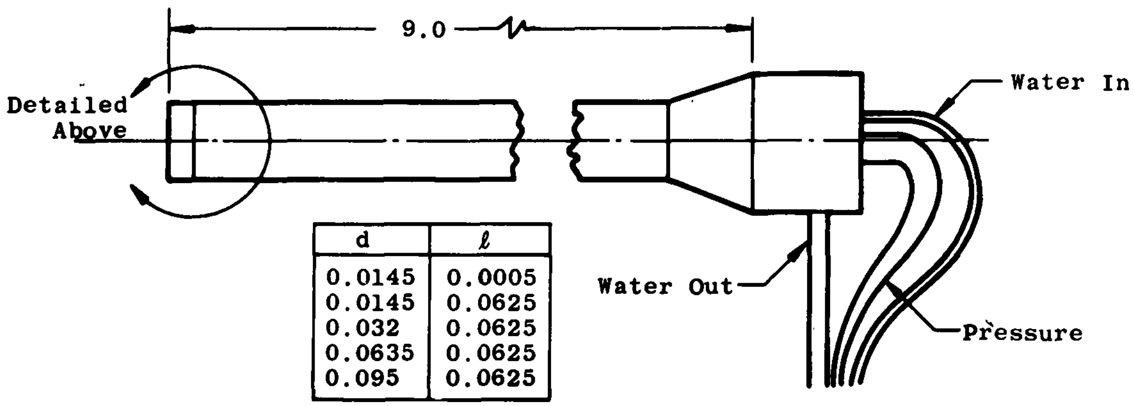
D	d	I.D.	ℓ
0.1265	0.0145	0.0963	0.125
0.1265	0.032	0.0965	0.125
0.157	0.0145	0.117	0.125
0.1863	0.0145	0.1463	0.125
0.1869	0.032	0.1469	0.125
0.250	0.0145	0.186	0.125

D	d	ℓ
0.0206	0.0140	0.5
0.0325	0.0145	1.3
0.0325	0.0235	1.3
0.0325	0.0250	1.3
0.042	0.0145	1.3
0.042	0.027	1.3
0.052	0.0145	1.3
0.052	0.027	1.3
0.051	0.035	1.3
0.065	0.0145	1.3
0.064	0.027	1.3
0.065	0.047	1.3
0.0865	0.066	2.0
0.0945	0.0637	2.0
0.095	0.071	2.0
0.100	0.075	2.0

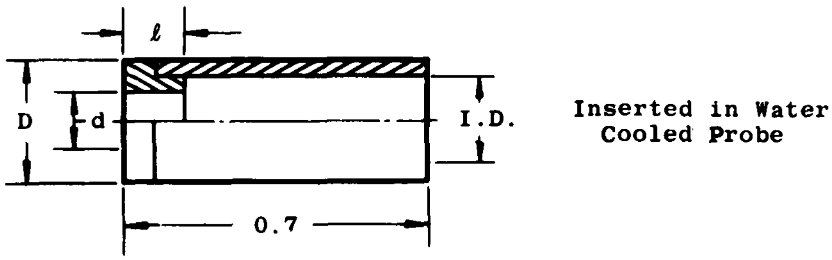
TABLE 1 (Concluded)



Detail of Water Cooled Probe Construction



d	ℓ
0.0145	0.0005
0.0145	0.0625
0.032	0.0625
0.0635	0.0625
0.095	0.0625



D	d	I.D.	ℓ
0.065	0.047	0.047	0.7
0.064	0.027	0.047	0.0625
0.064	0.027	0.027	0.7

TABLE 2

TEST RESULTS

Probe Outside Diam, D	Orifice Diam, d	$\frac{d}{D}$	Re_1 based on D	p_o', microns Hg	
0.503	0.484	0.9622	130.8	2280	
0.501	0.436	0.8703	130.3	2291	
0.501	0.375	0.7485	130.3	2306	
0.499	0.250	0.5010	129.7	2303	
0.499	0.250	0.5010	129.7	2314	
0.496	0.152	0.3065	129.0	2314	
0.500	0.104	0.2080	130.0	2314	
0.502	0.055	0.1096	130.5	2271	
0.500	0.0145	0.0290	130.0	2159	
0.375	0.3595	0.9587	97.5	2243	
0.376	0.311	0.8271	97.8	2237	
0.376	0.311	0.8271	97.8	2258	
0.375	0.250	0.6667	97.5	2280	
0.375	0.250	0.6667	97.5	2306	
0.377	0.125	0.3316	98.0	2272	
0.377	0.0635	0.1684	98.0	2261	
0.375	0.032	0.0853	97.5	2230	
0.248	0.228	0.9194	64.5	2310	
0.248	0.186	0.7500	64.5	2310	
0.247	0.125	0.5061	64.2	2316	
0.247	0.0635	0.2571	64.2	2225	
0.247	0.032	0.1256	64.2	2164	
0.250	0.032	0.1280	65.4	2193	
0.2475	0.0145	0.0585	64.4	2038	
0.250	0.095	0.3800	65.0	2291	Water Cooled
0.247	0.0635	0.2571	64.2	2277	
0.250	0.032	0.1280	65.0	2251	
0.250	0.032	0.1280	65.0	2219	
0.250	0.0145	0.0580	65.0	2095	
0.250	0.0145	0.0580	65.0	1998	
0.1845	0.178	0.9648	48.0	2305	
0.1885	0.1475	0.7825	49.0	2305	
0.1875	0.1175	0.6267	48.8	2288	
0.1875	0.0635	0.3387	48.8	2200	
0.1869	0.032	0.1712	48.6	2138	
0.1863	0.0145	0.0778	48.4	1944	

TABLE 2 (Continued)

Probe Outside Diam, D	Orifice Diam, d	$\frac{d}{D}$	Re_1 based on D	p_o', microns Hg
0.157	0.144	0.9172	40.8	2335
0.156	0.116	0.7436	40.6	2305
0.156	0.0635	0.4070	40.6	2235
0.156	0.0635	0.4070	40.6	2186
0.156	0.032	0.2051	40.6	2155
0.156	0.032	0.2051	40.6	2126
0.157	0.0145	0.0924	40.8	2015
0.157	0.0145	0.0924	40.8	2045
0.123	0.116	0.9431	32.0	2334
0.123	0.116	0.9431	32.0	2324
0.1265	0.095	0.7510	32.9	2311
0.1265	0.095	0.7510	32.9	2324
0.1280	0.089	0.6953	33.3	2306
0.1280	0.089	0.6953	33.3	2302
0.1265	0.085	0.6719	32.9	2294
0.1265	0.085	0.6719	32.9	2294
0.1265	0.061	0.4822	32.9	2277
0.1265	0.061	0.4822	32.9	2236
0.1265	0.032	0.2530	32.9	2197
0.1265	0.0145	0.1148	32.8	2019
0.100	0.075	0.750	26.0	2350
0.095	0.071	0.7474	24.7	2362
0.0945	0.0637	0.6741	24.55	2386
0.0865	0.066	0.7630	22.50	2386
0.065	0.047	0.7231	16.9	2386
0.065	0.047	0.7231	16.9	2391
0.065	0.047	0.7231	16.9	2412
0.065	0.047	0.7231	16.9	2396
0.065	0.047	0.7231	16.9	2321
0.065	0.047	0.7231	16.9	2295
0.064	0.027	0.4219	16.6	2303
0.064	0.027	0.4219	16.6	2324
0.064	0.027	0.4219	16.6	2330
0.064	0.027	0.4219	16.6	2229
0.064	0.027	0.4219	16.6	2190
0.065	0.0145	0.2231	16.9	2214

TABLE 2 (Concluded)

Probe Outside Diam, D	Orifice Diam, d	$\frac{d}{D}$	Re_1 based on D	p_o', microns Hg
0.051	0.035	0.6863	13.3	2441
0.051	0.035	0.6863	13.3	2448
0.051	0.035	0.6863	13.3	2433
0.052	0.027	0.5193	13.52	2324
0.052	0.0145	0.2788	13.52	2199
0.042	0.027	0.643	10.9	2498
0.042	0.027	0.643	10.9	2400
0.042	0.0145	0.3452	10.9	2241
0.042	0.0145	0.3452	10.9	2225
0.0325	0.0235	0.7232	8.45	2498
0.0325	0.0250	0.7692	8.45	2453
0.0325	0.0145	0.4462	8.45	2324
0.0206	0.014	0.6796	5.36	2661
0.0206	0.014	0.6796	5.36	2655
0.0206	0.014	0.6796	5.36	2598

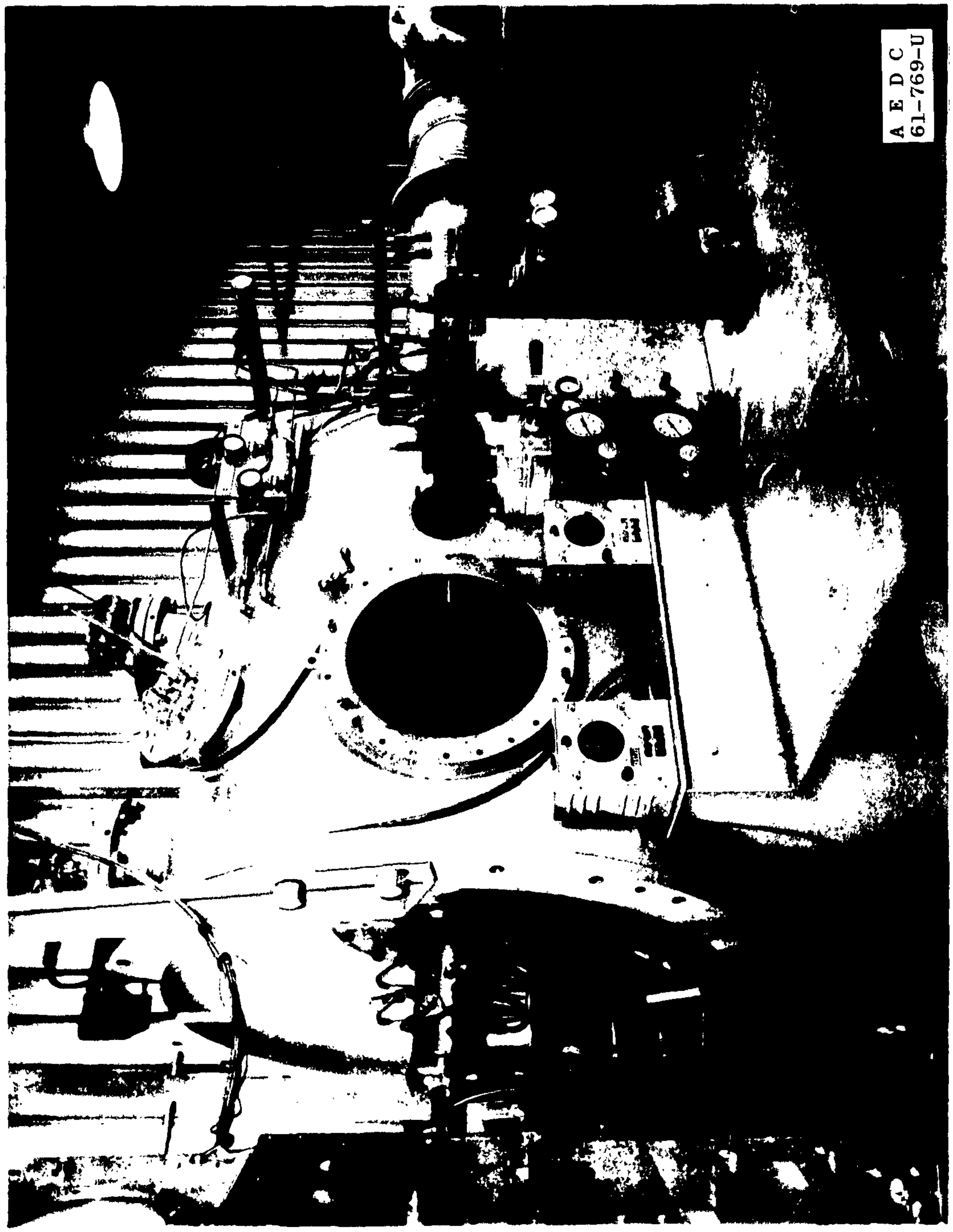


Fig. 1 Photograph of the LDH Wind Tunnel

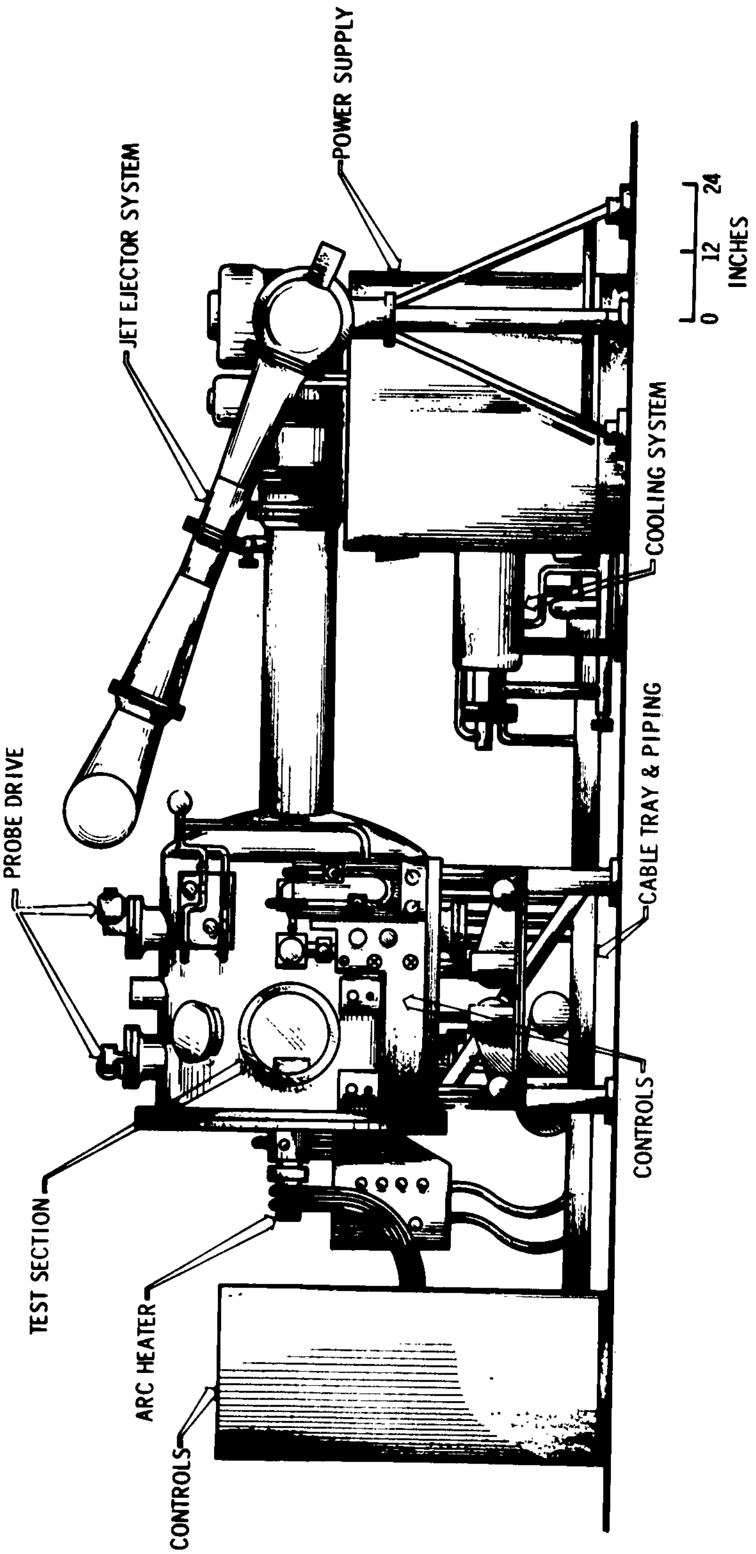


Fig. 2 Elevation View of the LDH Wind Tunnel with Major Components Identified

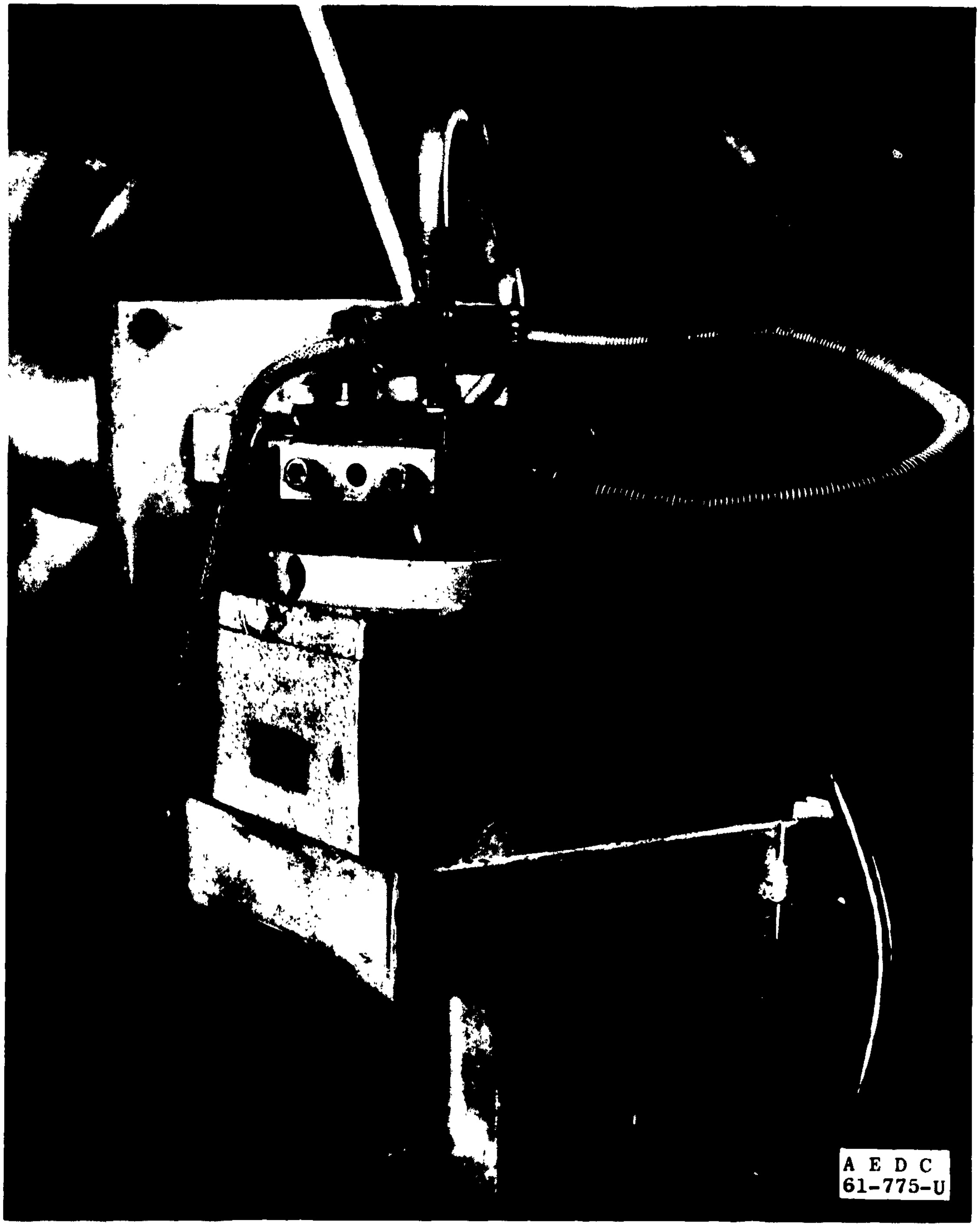


Fig. 3 Transducer Mounted on the Rotary Valve

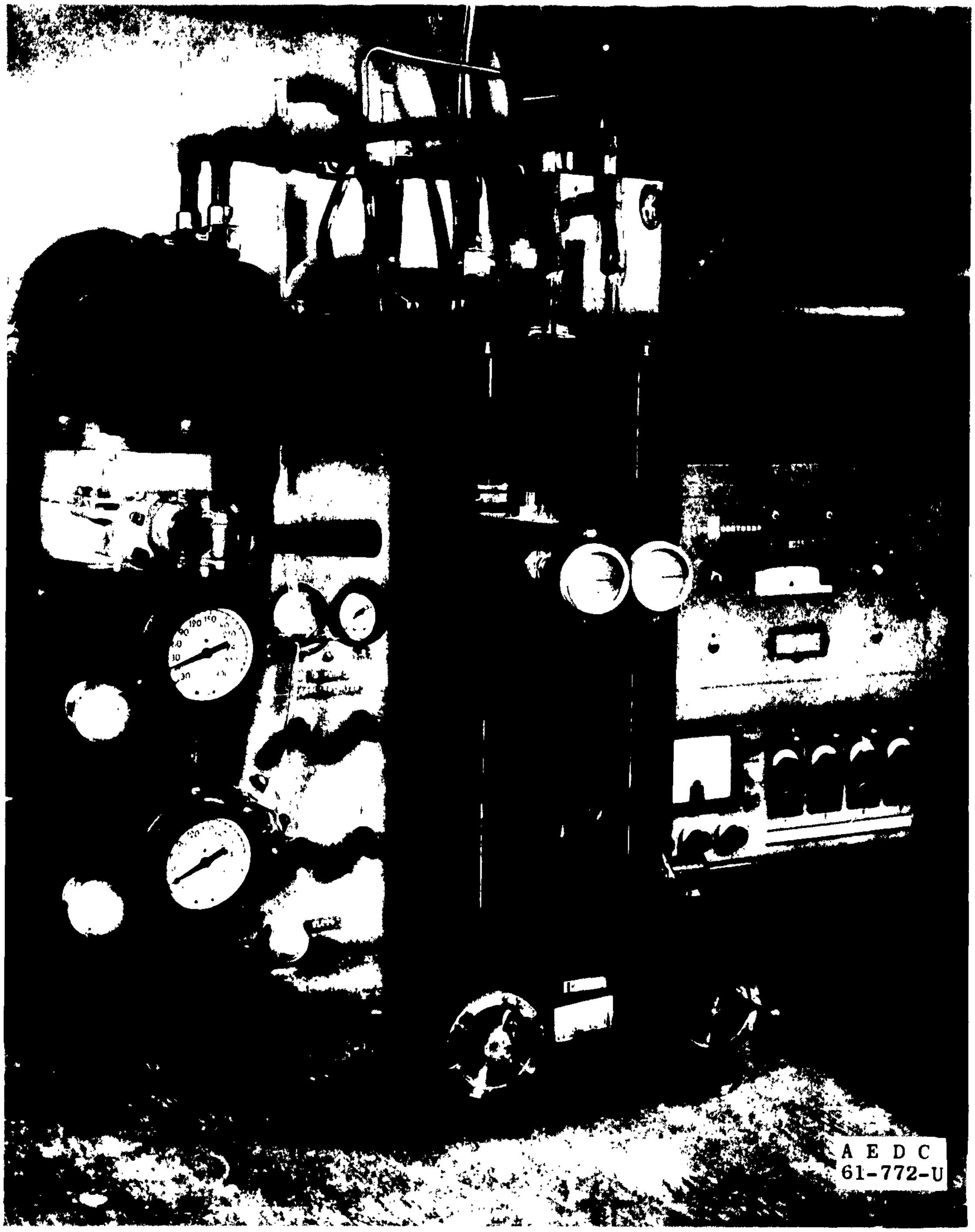


Fig. 4 Precision Micromanometer with Pressure Reference and Calibration Headers

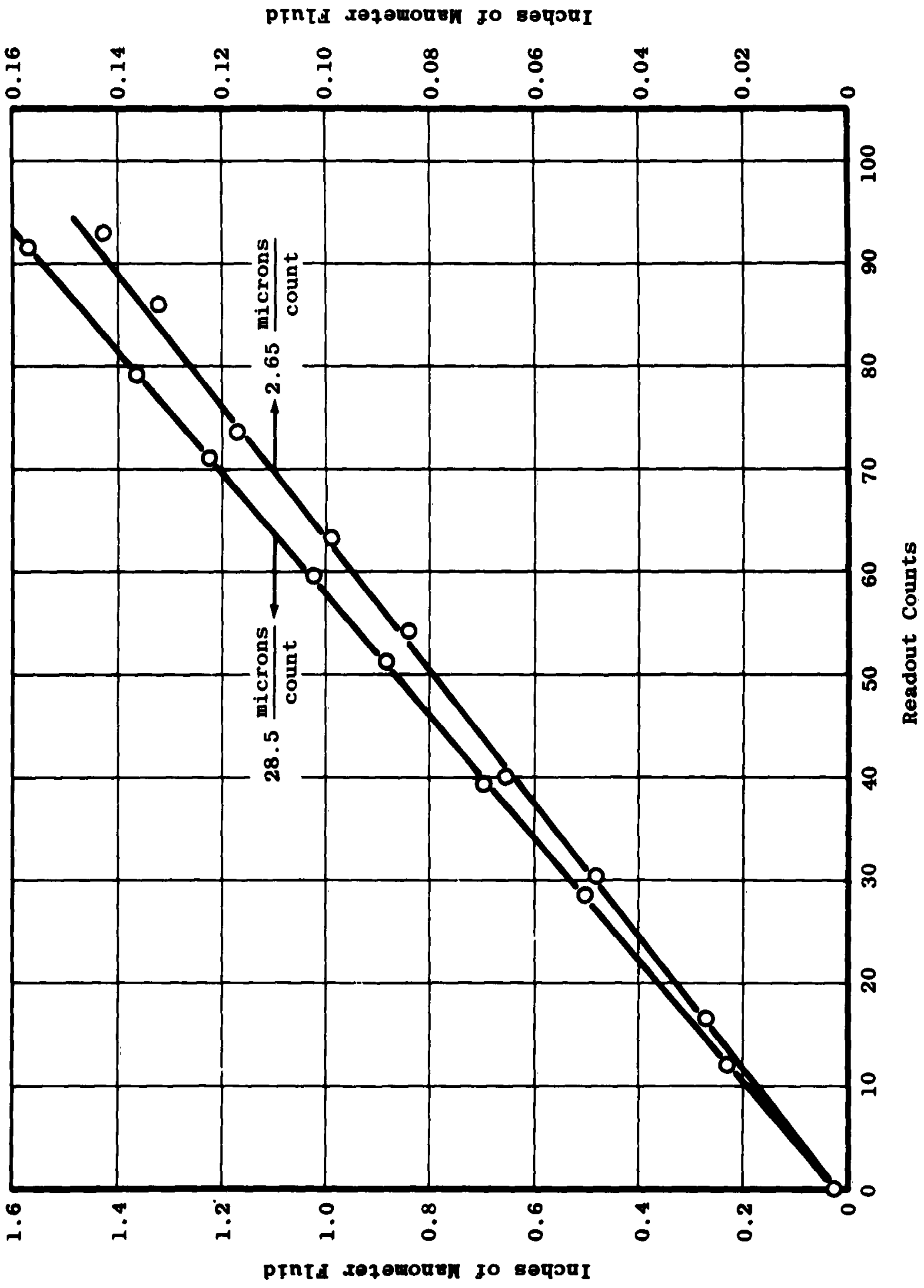


Fig. 5 Typical Transducer Calibration

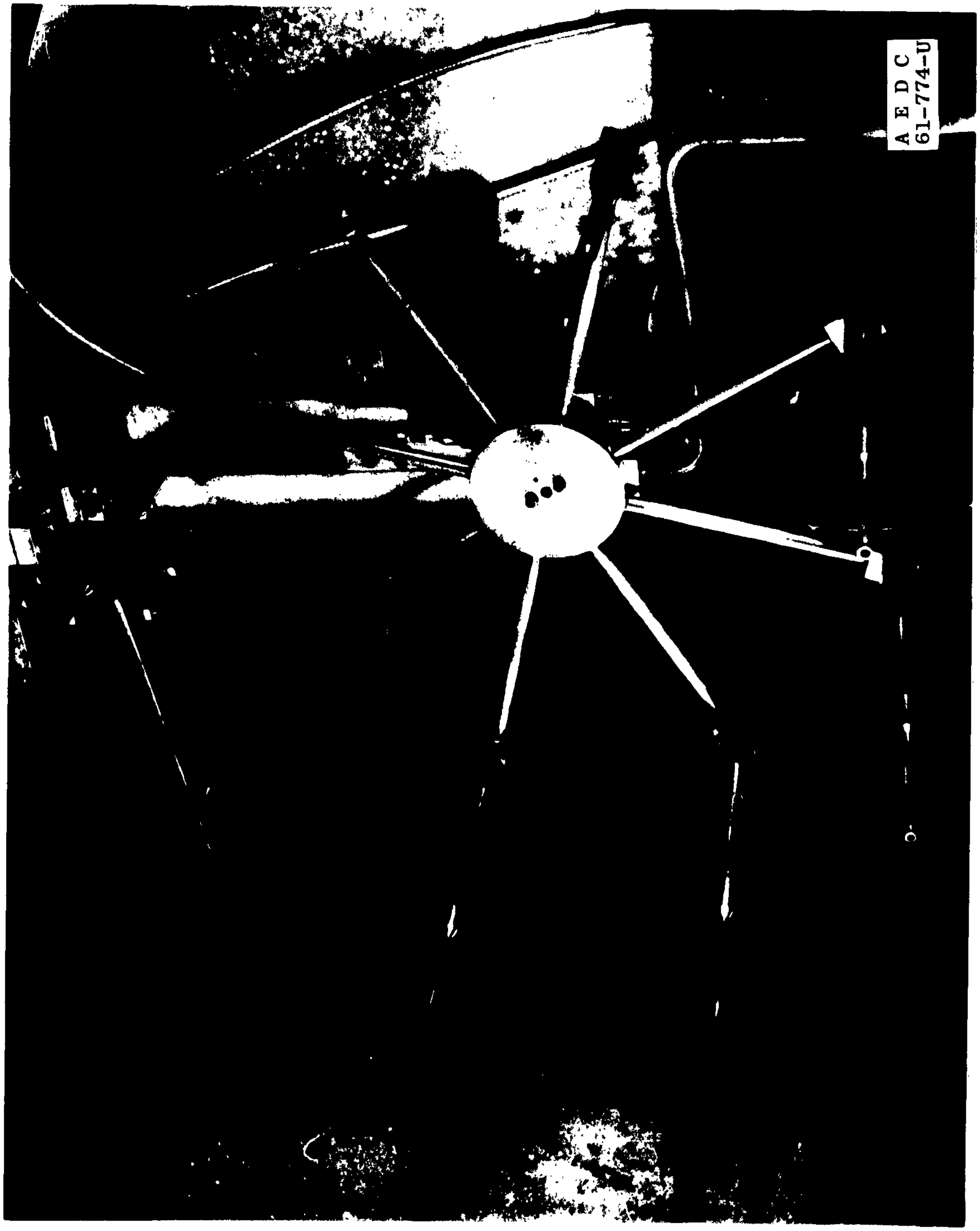


Fig. 6 Rotary Probe Holder with Probes Attached

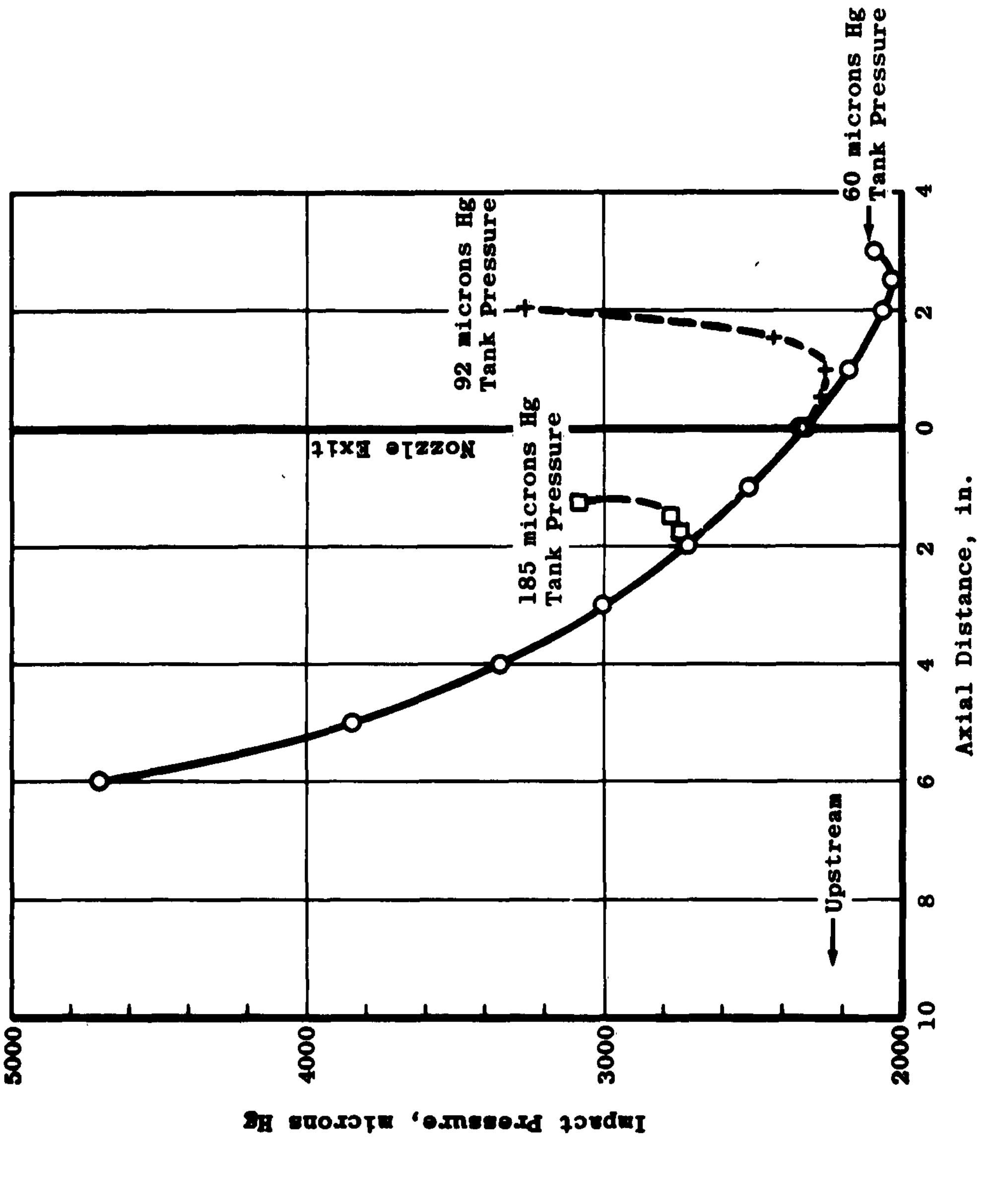


Fig. 7 Impact-Pressure Variations along the Nozzle Centerline at Various Test Chamber Pressures

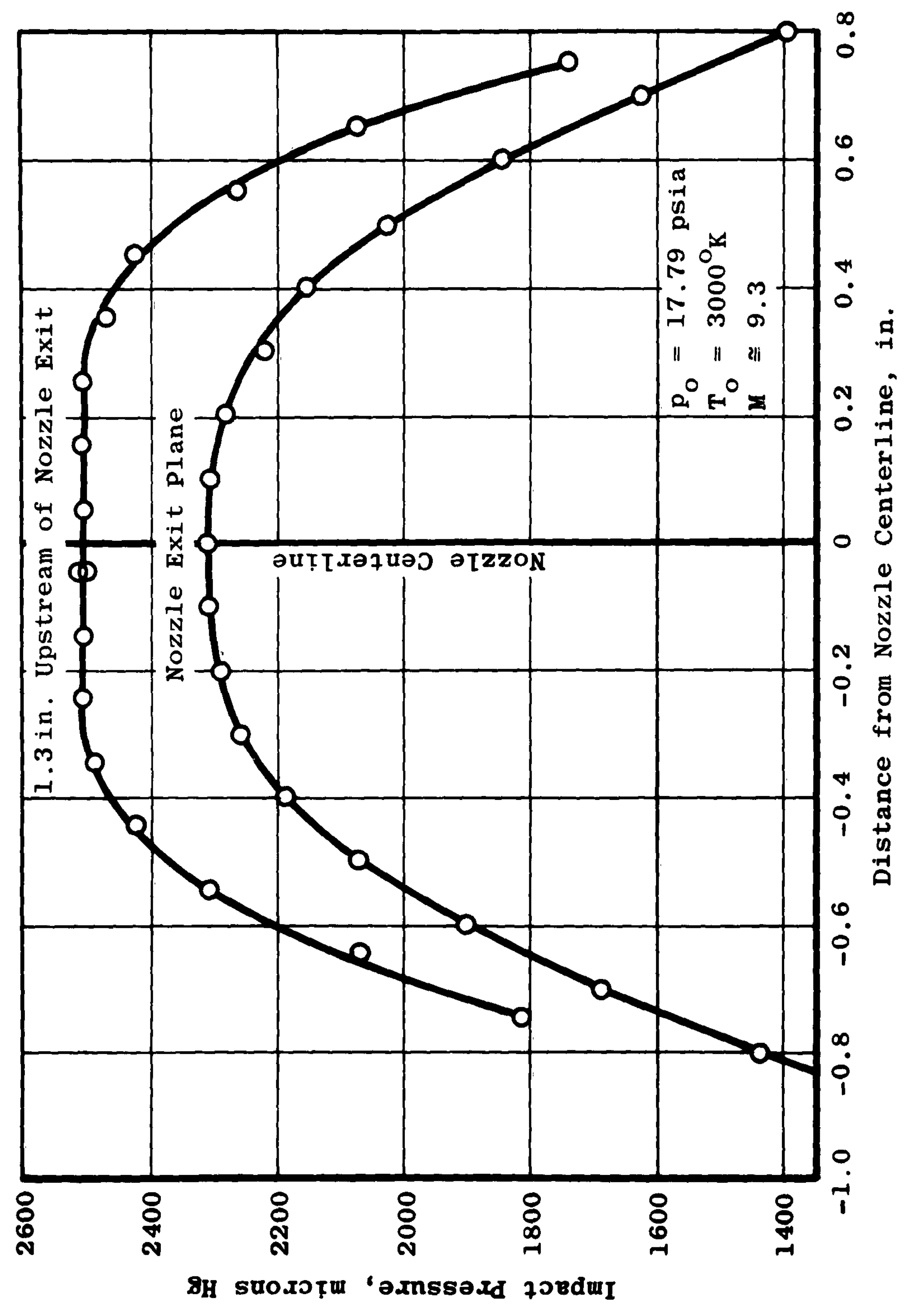


Fig. 8 Impact-Pressure Profiles in the Test Region

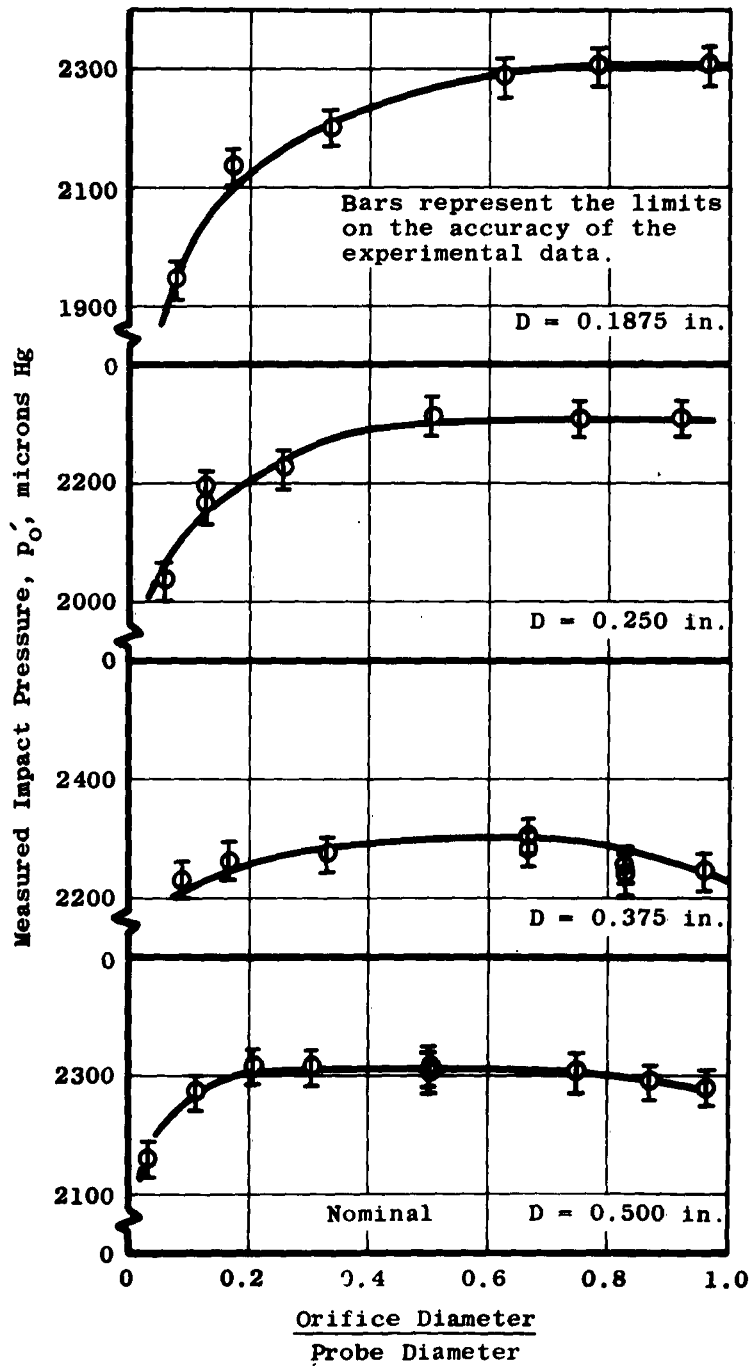


Fig. 9 Variation of Measured Impact Pressure with Orifice-to-Probe Diameter Ratio

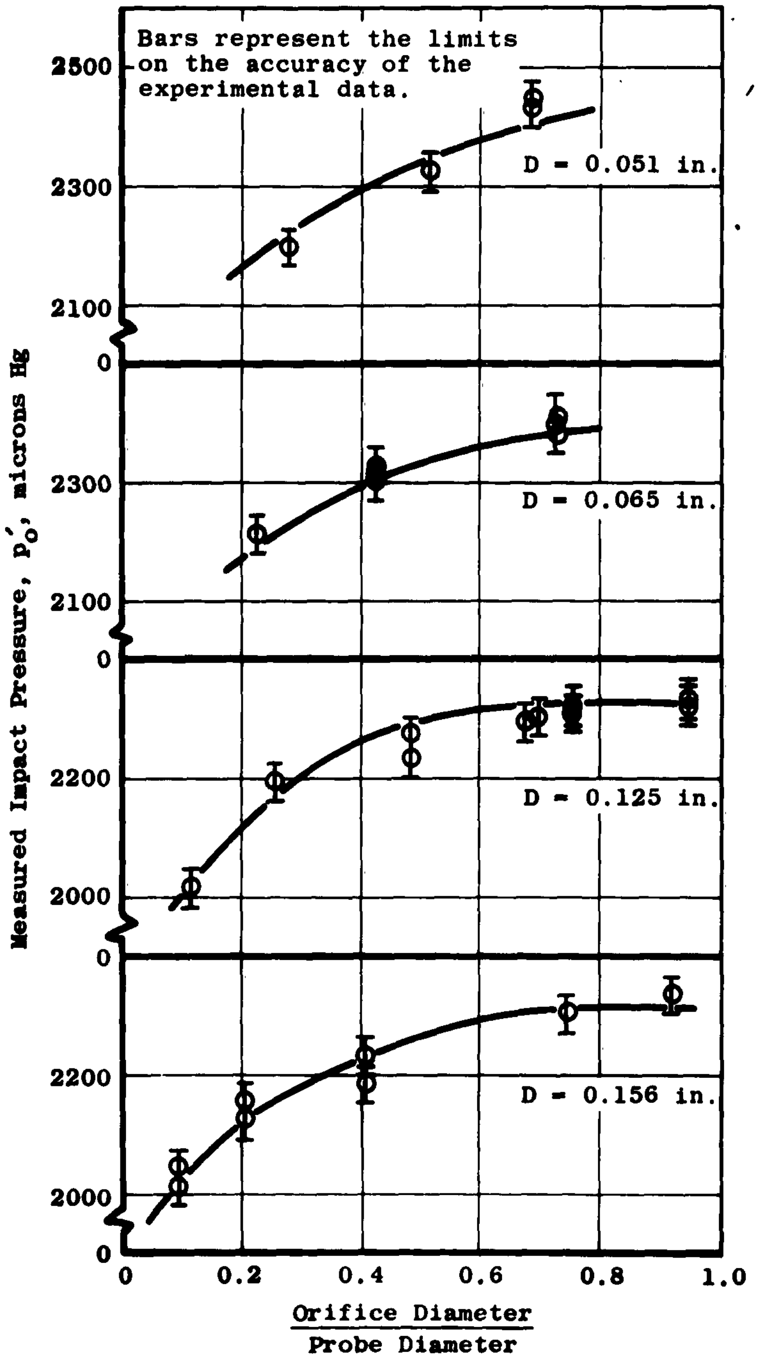


Fig. 9 Continued

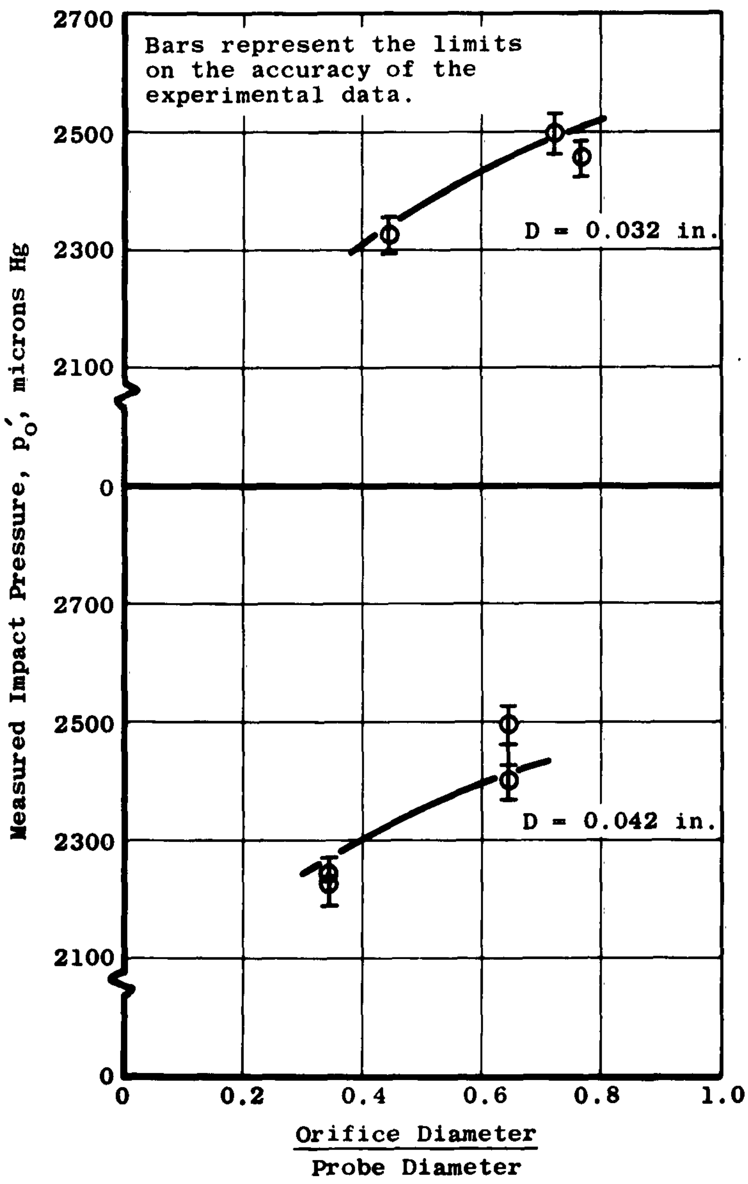


Fig. 9 Concluded

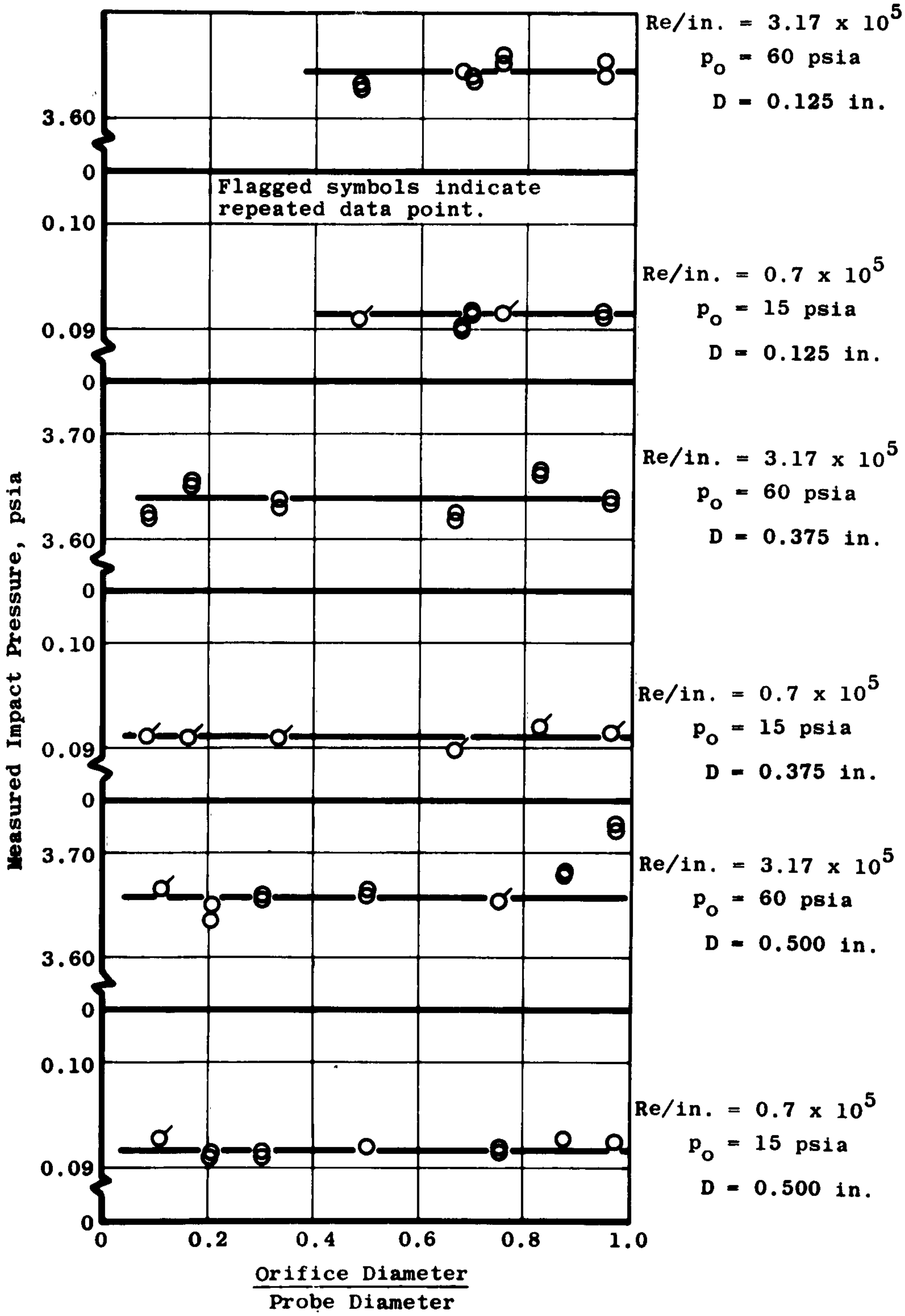


Fig. 10 Variation of Impact Pressure with Orifice-to-Probe Diameter Ratio at M = 5.0 and Higher Reynolds Numbers

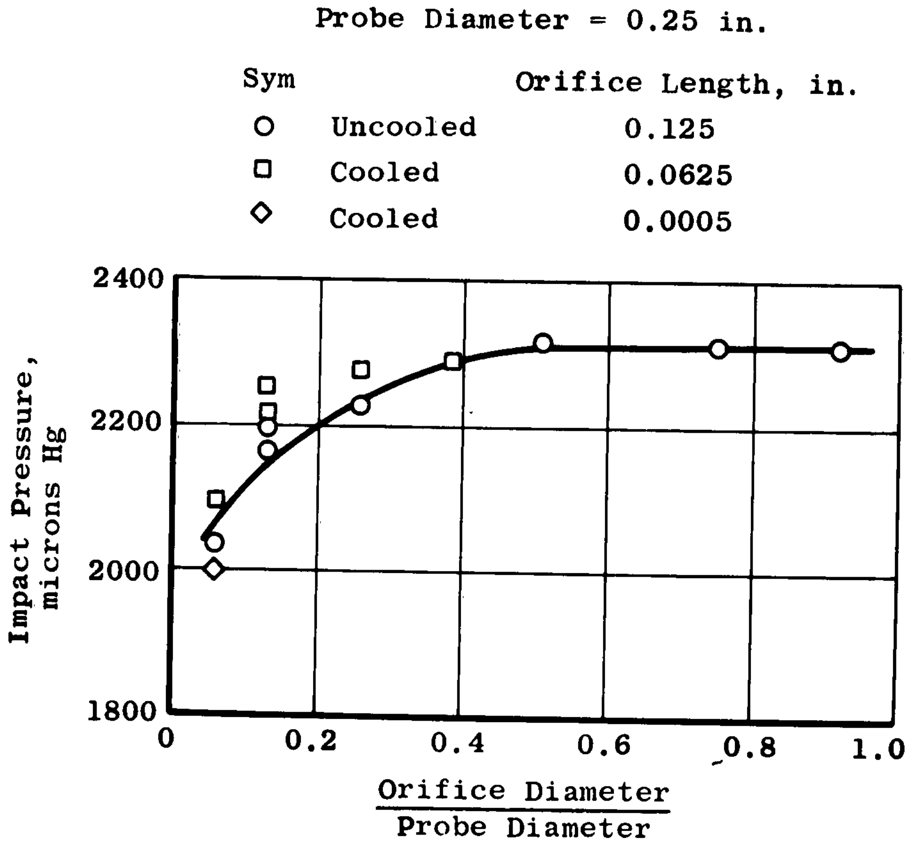


Fig. 11 Effect of Water Cooling the Impact Probe on the Measured Impact Pressure

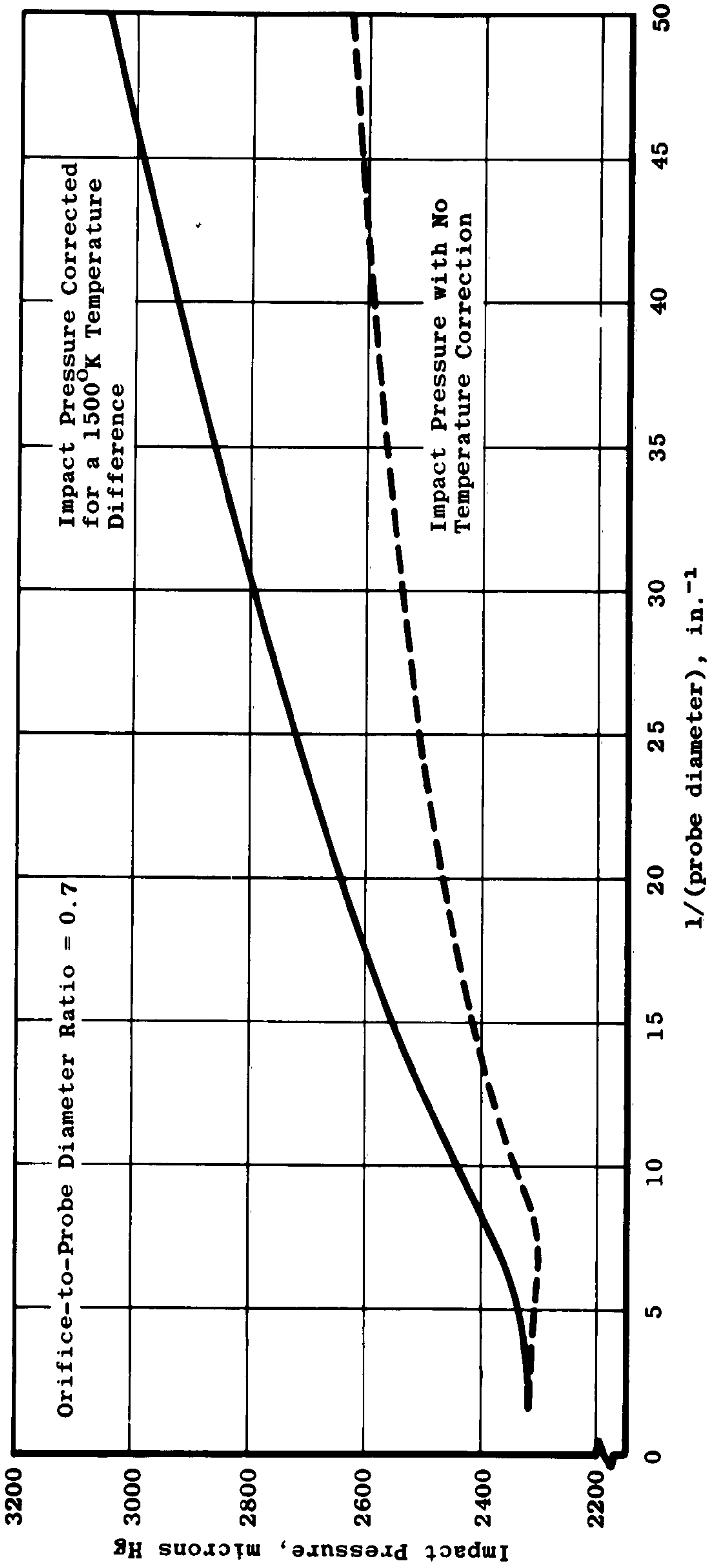


Fig. 12 Variation of Impact Pressure with Probe Diameter

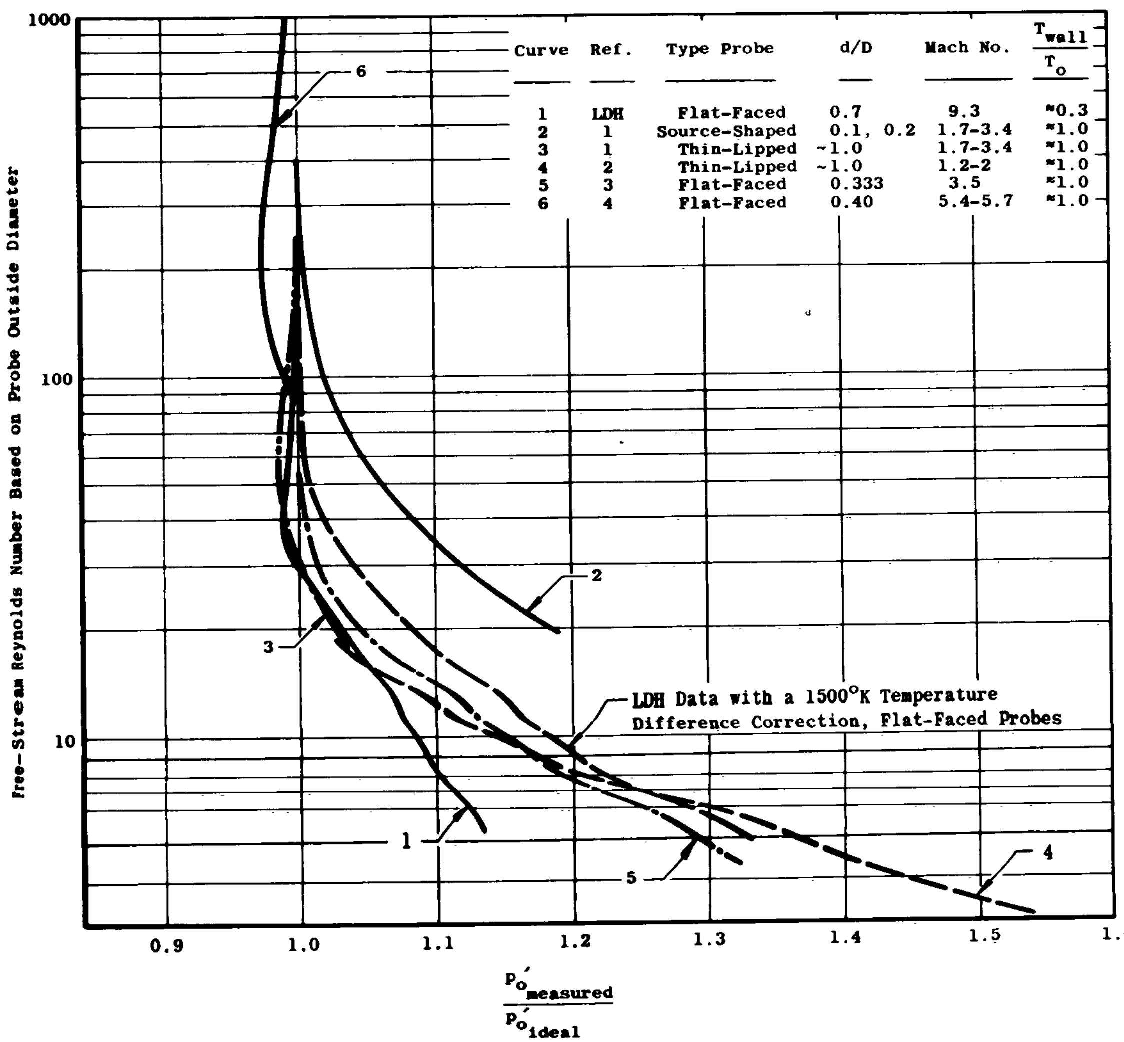


Fig. 13 Comparison of Impact-Pressure Measurements at Low Reynolds Numbers

Cut on broken line

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